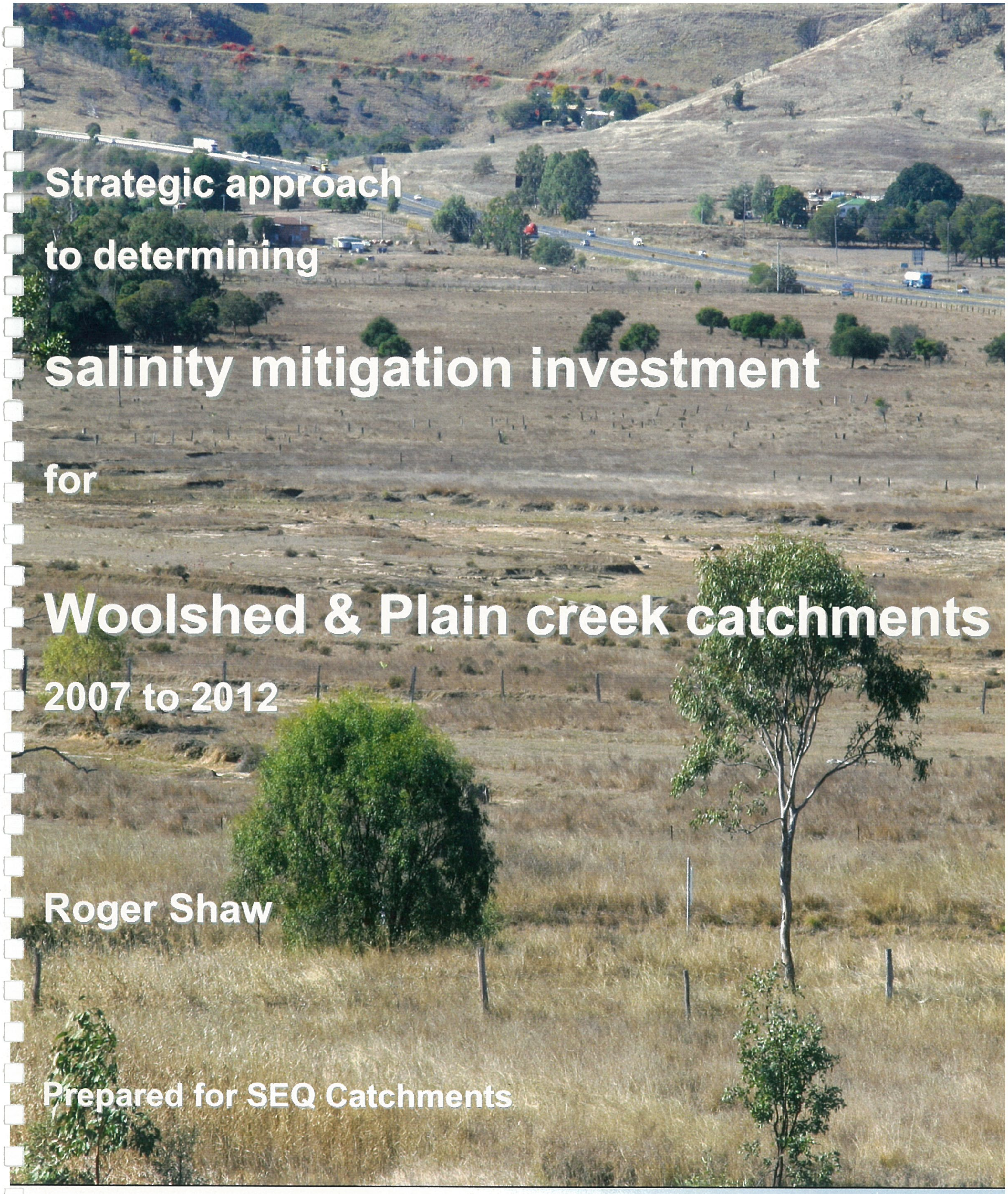

Strategic approach to determining salinity mitigation investment for Woolshed & Plain creek catchments

2007 to 2012

Roger Shaw

Prepared for SEQ Catchments

SEQ Catchments

Healthy land – healthy water

Strategic approach

to determining

salinity mitigation investment

for

Woolshed and Plain creek catchments

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Final report

April 2007

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Strategic approach to determining salinity mitigation investment for Woolshed and Plain creek catchments 2007 to 2012

Summary

Woolshed and Plain Creeks show salting outbreaks and also very high groundwater salinity in the northern parts of the catchments. While these salt issues have been present for many years, there is a need to determine the priority management actions that will result in a sustainable reduction in the impacts of salinity over the longer term. The salinity processes operating in Woolshed and Plain Creeks are consistent with those of the rest of the Lockyer Valley that have been validated through previous studies. This means that sensitive areas in the catchment can be readily identified. The conclusion is that both Woolshed and Plain Creek catchments are essentially semi-closed basins with very limited discharge of groundwater out of the catchments. Both catchments are under very significant salinity stress and it is predicted that a small change in extra recharge of the groundwater will result in extensive areas of very saline and bare areas that will be very difficult to manage because of the quantities of water and salt involved and the impact of the existing and emerging pressures on the hydrology of the catchments.

These additional pressures are influencing salinity, even in the period of dry rainfall years. The main pressures are: increased dams which have a history of leaking and filling the unsaturated storage with water resulting in surface evaporation and salting and also local recharge of groundwater, increasing areas of non-sewered subdivisions which increases the hydraulic loadings on the catchments substantially increasing groundwater recharge and creating salinity issues, and the extensive siltation of existing stream channels reducing natural groundwater drainage and resulting in shallower saline groundwater particularly in the northern ends of the catchments.

A stage of salinity development and reclamation process has been used to map salinity risk for the catchment. Together with the implications of a change of state from a non-salted to salted catchment and knowledge of the different processes operating, proactive actions have been identified for critical salinity areas of the catchments. To restore a salt affected area means changes are required at the same time to: reduce soil salinity levels in the root zone to below the critical soil salinity value, and, reduce the degree of groundwater imbalance to lower the water table levels since water drives the system. Strategies and management actions have been identified for each of the salinity areas of the two catchments.

Three methods of prioritising management actions have been used to identify priority areas and a timetable for action to minimise further salinity developing and to reclaim existing saline areas where possible. Further investigations are suggested for some areas to ensure the proposed actions are effective and to minimise any unintended negative impacts.

Recommendations are outlined in the next section.

Recommendations

This report is for SEQ Catchments to consider the best options for co-investment to mitigate and reclaim salinity in the Woolshed and Plain Creek catchments. The following recommendations are made for consideration as a way to proactively address the salinity issues in these two catchments based on the analysis in this report.

1. Local area landholders meet in facilitated discussions to consider the implications of and agree to actions for the recommended management options for their local area.
2. The actions recommended for the most critical salinity risk areas in Tables 9 and 10 and sections 13 and 14 be agreed to and implemented at an early opportunity. Implementation before normal rainfall patterns return will give a major advantage in minimising further salinity degradation.
3. Some additional investigations are required to provide data to ensure the proposed actions are viable and minimise adverse consequences as outlined in Tables 10 and 14.
4. Monitoring is necessary to be able to evaluate the success of the proposed management options and to make any adjustments required before it is too late. Strategies are provided for this monitoring in Tables 9, 10 and 14 for the specific areas
5. There are serious implications on salinity development from non-sewered subdivision development and negotiations with local government is required to inform and seek options to minimise the impact from existing and further developments
6. The increasing numbers of farm dams are affecting the flushing of salts from the major streams and increasing recharge of the groundwater which is expected to make the salinity problems worse. Some water management plans for the catchments will be required to seek a balance between conflicting requirements
7. Adaptive management processes be followed because of the uncertainties of the prediction of outcomes, the need for a whole-of-catchment view of the impacts of the management actions in specific areas and to ensure defined times for review and assessment of progress and adjustment of strategies as may be required to ensure the whole plan is integrated and effective.

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Facilitator software to determine the priority order of options based on the linear optimisation of the scores for each option against the rank order of criteria from Table 13 using the individual scores of Table 11. The priority order is ranked based on the mean score for each option.

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1. Introduction

Salinity has been an issue in the Lockyer Valley catchment for many years. SEQ Catchments has several targets to meet in salinity management as part of the NHT2 and NAPSWQ funding and is seeking a strategic approach to determining where to best tackle salinity issues in Woolshed and Plain Creek catchments. There have been many previous studies on salinity aspects for the Lockyer Valley and some for Woolshed and Plain Creeks. People are motivated to address salinity at the very local scale which often leads to only short term improvements because the catchment scale issues and factors determining salinity are not adequately addressed. Also reclamation from a very saline degraded state is difficult because the degraded state has different processes operating and reclamation to a restored state doesn't occur unless some critical water and salinity levels can be achieved first.

This report provides a strategic overview of salinity processes and their applicability to the Lockyer Valley and Woolshed and Plain Creek catchments. It identifies preferred management options based on regional and catchment scale processes to manage the existing and emerging issues that may impact on landscape salinity in Woolshed and Plain Creeks in the future. Priorities are given on possible investments in Woolshed and Plain Creeks that will have a lasting impact on restoring lands degraded by salinity and also proactively minimising potential emerging salinity problems. Further investigations that may be required are identified.

2. Vision and objectives for salinity management

A proposed vision for the long term outcomes is: Investment in appropriate catchment management strategies can sustainably reverse or reduce the impacts of salinity degradation and proactively reduce the impacts of emerging pressures affecting salinity in Woolshed and Plain Creek catchments.

The objectives of this study are:

- to provide a firm foundation to invest in salinity mitigation in the Woolshed and Plain Creek catchments based on the principles of salinity processes and effective remediation
- Outline a transparent prioritisation process for sites and reclamation options based on the following:
    - Clarification of salting processes operating in the catchments.
    - Maps of the catchment showing stages of salinity development and reclamation with possible management options.
    - Decision criteria for choosing prioritised management actions based on severity of impacts and expected benefits.
    - Prioritisation of areas for salinity mitigation actions.

3. Overview of salinity relevant to the Lockyer Valley catchment

Salinity development and reclamation have been described in detail for Queensland in Salcon (1997). Important aspects for the Lockyer Valley catchment and the processes directly relevant to Woolshed and Plain Creeks are given here as the basis for deciding on the most appropriate methods for intervention to reduce the current and future effects of salinity.

3.1 Salinity

Salinity is an issue in natural resource management because it reduces the potential productivity and use of land and water resources. **Salinity** by definition is the presence of soluble salts in soils or waters. Salinity processes are natural processes of landscape and soil formation. However, human activities can contribute to salinity and long-term land and water degradation. Salinity usually becomes a land use issue when the concentration of salt or sodium adversely affects plant growth (crops, pastures, or native vegetation), degrades soil structure or causes soil erosion. It becomes a water issue when the potential use of a water is limited by its salt content or its salt composition.

Salts are the dissolved material from the weathering of the earth's crust. These dissolved materials also include dissolved silica, iron, manganese and other heavy metals which rarely remain in solution as the concentration increases. The more soluble the salts the more they contribute to landscape salinity. The most common salts and their solubility in water are given in Table 1 showing the very wide range of solubility which increases moving down the table. As the salt concentration increases or the solution evaporates, the lowest solubility salts precipitate out of solution first. Generally only salts more soluble than gypsum are a problem for landscape salinity. Because the less soluble calcium and magnesium salts precipitate out of solution first as the concentration increases, there is a change in salt composition with increasing salt concentration. As the salt solution becomes more and more concentrated, the salt composition for many waters approximates seawater dominated by sodium chloride. However, for waters sourced from basalt geology, magnesium and sometimes calcium are of higher relative concentration than sodium and may remain in solution at higher salt concentrations. This is the case for the southern tributaries of Lockyer Creek.

The relative composition of salts is as important in the use of particular waters as the total salt content. Generally waters high in sodium will cause problems in soils leading to erosion, soil dispersion and instability, surface crusting, limited soil wetting, low water holding capacity as well as soil structural degradation, poor plant growth and productivity. Waters higher in calcium and magnesium concentrations are more useable at higher salt concentrations.

Table 1. Solubility of common salts in water. The solubility of carbonate and bicarbonate salts depends on the concentration of carbon dioxide.

Salt	**Common name**	**Solubility** $\text{millimoles}_{\text{charge}}$ **/L**
Calcium carbonate	Lime	0.5
Magnesium carbonate	Dolomite	2.5
Calcium bicarbonate		3-12
Magnesium bicarbonate		15-20
Calcium sulphate	**Gypsum**	**30**
Sodium sulphate	Glauber's salt	683
Sodium bicarbonate	Bicarb of soda	1 642
Magnesium sulphate	Epsom salts	5 760
Sodium chloride	Common salt	6 108
Magnesium chloride		14 955
Calcium chloride		25 470

Source: modified from Doneen (1975).

Salt concentration of soils and waters increases in three ways:

1. when water evaporates, the salts are left behind and if there is limited seasonal flushing, the salts accumulate. Lake Eyre is a classic example.
2. when plants transpire water from the soil and leave salts behind in the root zone. This is normal. Whether the salt level is an issue depends on whether there is a shallow

watertable present (as a source of water and salts) or accumulated salts can be slowly moved downwards by rainfall.
3. when groundwater moves through aquifers or soils and weathering of rocks or dissolution of salts occurs in the moving water. The Great Artesian Basin waters are a classic example.

Landscape salinity occurs when the rate of groundwater recharge exceeds the rate of groundwater use and/or flow out of a catchment resulting in salt concentration. The term landscape salinity is used to refer to salinity at the landscape scale which includes naturally occurring salinity, human induced salinity and water salinity.

There is a continuum between the balance of groundwater recharge, groundwater outflow and use, and landscape salinity as follows:

- if depth to groundwater is greater than 3 metres and outflow and use exceed groundwater recharge, watertables are generally too deep for accumulation of salts in soils. This is a normal situation.
- if groundwater outflow and use are less than groundwater recharge, shallow watertables will often occur with associated salinity
- if groundwater outflow and use are considerably less than groundwater recharge, flushing of accumulated salt occurs and waterlogged or wetland areas develop of generally low salinity. An example of this last situation is given in Photo 1.

Photo 1. Example of a catchment where groundwater seepage flushes accumulated salts resulting in a non saline and waterlogged area (from the Eastern Darling Downs).

3.2 *Productive use from saline soils and waters*

Soils and waters containing reasonable levels of salinity can be used productively depending on the total salt content, the composition of the salts and the purpose of use. Sodium is particularly deleterious to soil structure and soil behaviour. Figure 1 shows the potential use of waters with a given salt content. A similar figure can be derived for soil salinity with knowledge of the change in salt content with depth in the soil. Figure 1 uses units for salt content based on measuring the electrical conductivity of a water sample. This is an easy and direct method and very commonly used. Simple conversions to salt content in other units are given in Table 2.

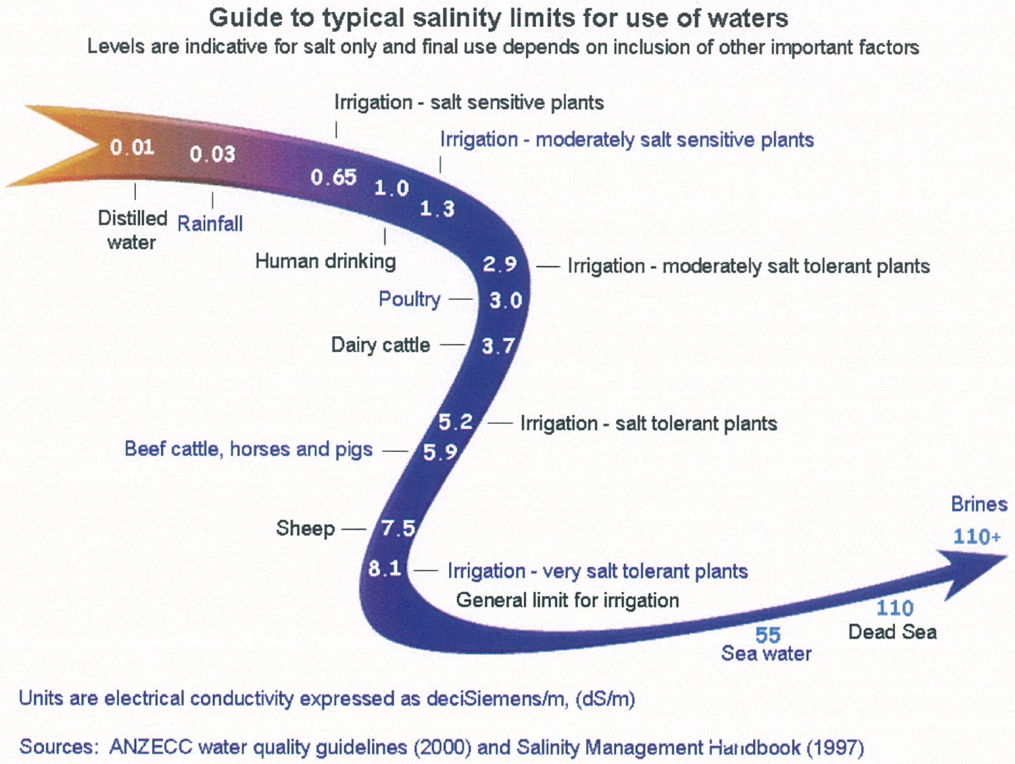

Figure 1. Guide to use of waters with increasing salt content. The composition of the salts needs to be considered for many of the applications. For human and domestic use, additional analyses are required for assessment of the suitability of a water for an intended use.

Table 2. Conversions between common units of salinity.

From	To		
	EC mS/cm ≡EC dS/m	**EC µS/cm**	**Total dissolved ions mg/L or ppm**
EC dS/m	1	1 000	2/3 mult 1 000
mg/L (ppm)	Divide by 1 000, mult 1.5	1.5	1

3.3 Processes of salinity in the landscape

Salinity is visible at the soil surface when water containing salts is evaporated, or in a stream bank where seepage from groundwater occurs. Under natural situations before European settlement, catchments were generally in some varying equilibrium with rainfall, groundwater recharge, and the groundwater outputs by evaporation, transpiration by plants, stream flow and groundwater flow out of a catchment. Vegetation was the buffer in the system and largely accommodated the varying rainfall patterns and groundwater level fluctuations. In areas that were more continuously wet, increased vegetation density occurred with species that could withstand wetness and/or higher salt content. Where salting occurred and vegetation died, erosion of the bare surface resulted in gullies, increased the depth to the water table by drainage and reduced the salt concentration in the soil at the same time. Plants could then regrow and stabilise the area.

Since groundwater is the major driving influence on the expression of landscape salinity we can consider the processes in a catchment as shown in Figure 2. Where there is some natural or human made restriction to groundwater flow out of a catchment, and the inflow of water through recharge below the root zone is greater than the ability of groundwater to flow out of the catchment, salinity or waterlogging will occur. The extent of the groundwater imbalance is approximately indicated by the salt affected or waterlogged area. The restriction to groundwater flow may be low aquifer transmission properties, a physical barrier such as resistant rock formation or a very low hydraulic gradient, resulting in reduced lateral flow of groundwater. The distance between a recharge area and discharge area can be short, tens of metres to thousands of kilometres as for the Great Artesian Basin.

Salts are deposited on the soil surface by evaporation through capillary rise through the soil (like a wick) from a shallow water table or where plants transpire the water and leave the salts behind and then a gradually rising water level moves those salts to the soil surface. Generally if groundwater moves upwards through the soil at a rate greater than the evaporation rate, it will flush away the accumulated salts at the soil surface giving a wet area or seep with little to moderate salt content unless the groundwater is particularly salty.

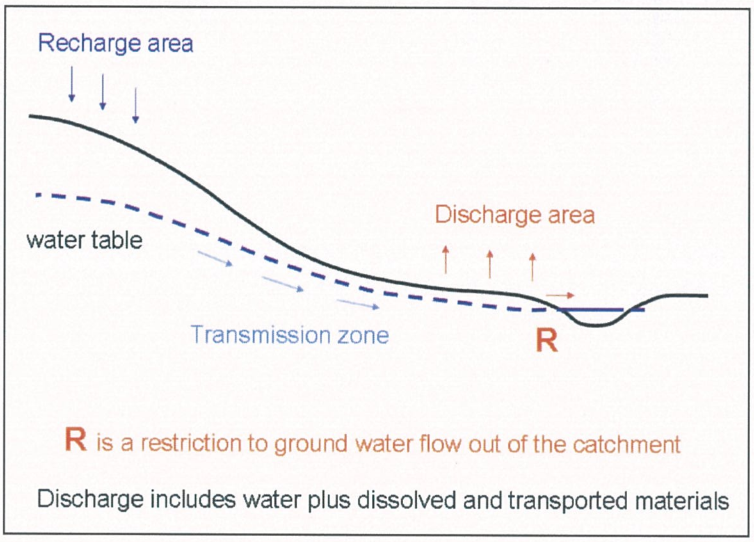

Figure 2. A simple model of groundwater processes in a catchment illustrating recharge, transmission and discharge zones where there is evaporation in the discharge area from a shallow water table. Figure based on Salcon (1997).

Figure 3 shows the typical salt content profiles in the top 2 metres of soils for recharge, normal, discharge and intermittent discharge areas. The shape of the profiles is a reflection of the dominant source of water whether rainfall or a shallow water table. Recharge areas are permeable or fractured rock areas with limited salt accumulation because the water moves through the soil quickly. Normal profiles reflect the result of plant transpiration where the source of water is rainfall. Salt accumulates most at the bottom of the active root zone depth. On clearing or irrigation with surface water, the salt in the soil is leached downwards to a new equilibrium salt profile with less salt. The red dotted line for discharge areas is typical of regions of shallow water tables where the dominant source of water is from the water table with evaporation at the soil surface.

The intermittent discharge profile is typical of situations with alternating periods of shallow water tables followed by rainfall which flushes the accumulated salts down to the groundwater and the surface accumulated salts away through surface flow. This usually follows a series of years of alternating higher and lower rainfalls. Figure 4 illustrates the impact of irrigation together with episodic cyclones on the salt content of the groundwater for the lower Burdekin region. Salts in the soil and unsaturated layers above the water table have been moved into the groundwater.

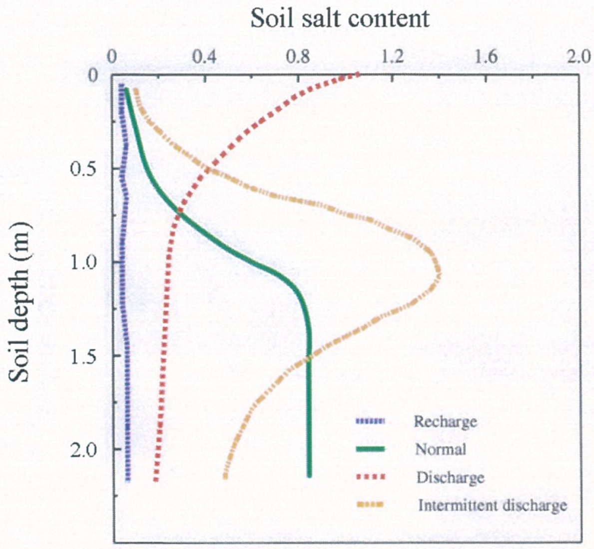

Figure 3. Idealised shape of salt concentration with soil depth for recharge, normal, discharge and intermittent discharge areas. Figure based on Salcon (1997).

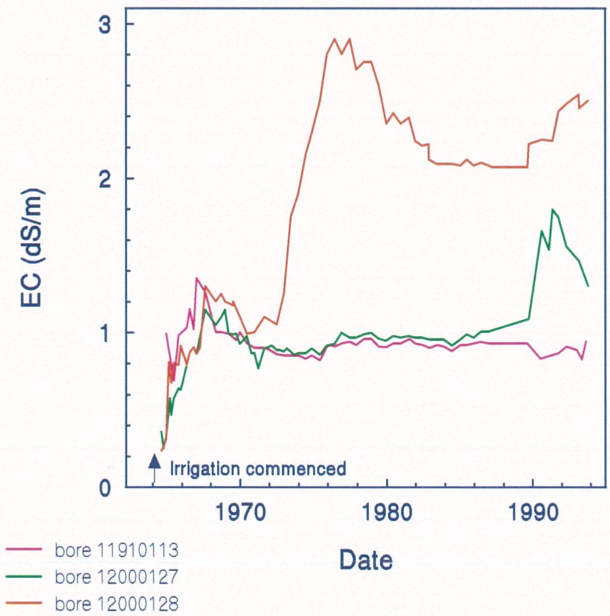

Figure 4. Effect of irrigation and episodic cyclones on salt concentration in the groundwater due to leaching of salt from the soil profile. Data courtesy of Department of Natural Resources and Water.

The depth to the water table and the salt content of the groundwater determine the concentration of salts at the soil surface with evaporation as illustrated in Figure 5 for the lower Burdekin region. From Figure 5, maximum salt concentration occurs in a depth range where capillary rise from the water table to the soil surface is most efficient. As the depth increases, the rate of capillary rise is reduced which reduces the salt concentration at the soil surface. Where the water table depth is at or very close to the soil surface, flushing of the salts occurs and the salinity more closely reflects that of the groundwater or even less than groundwater salinity depending on rainfall. The high salt content of the groundwater in this figure occurs between 1 to 4 metres depth to the water table. The range reflects the fluctuating water table levels and the periodic movement of salts on the soil surface and upper root zone down to the water table under rainfall. The implications are that soils above a very saline water table will not be affected to any significant degree provided the depth to the water table is greater than about 4 to 5 metres for most of the time. Generally a depth of 2 metres to the water table is considered very marginal in salinity risk areas and likely to cause surface salting depending on soil texture.

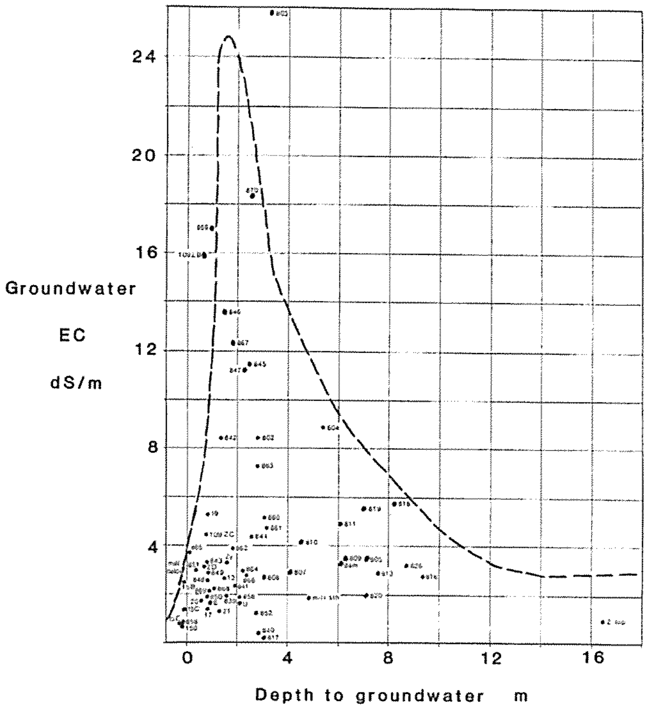

Figure 5. Relationship between depth to the watertable and the salinity of the water table for the lower Burdekin region from Shaw *et al.* (1987).

Evaporation of groundwater from bare salted areas is the way the catchment tries to come to groundwater equilibrium with any additional water inputs in the absence of the vegetation buffer. The relationship with depth is illustrated in Figure 6. It is not as efficient a process as evaporation from exposed free water because salt accumulates and affects soil structure and evaporation rate. As a guide to the Lockyer Valley region, normal evaporation is around 1 500 mm/year and together with rainfall, soil with seepage water on the surface may be expected to evaporate around 1 000 mm per year, illustrated by the small arrow on the right hand axis of Figure 6. The relationship with depth to the water table is very evident for the salt pan (red dots). In Figure 6, the vegetation (green dots) would be using water of lower salinity than most salted areas. As the salt concentration in the soil increases, vegetation reduces its ability to transpire water because it has to expend considerable energy to overcome the osmotic potential of the soil solution generated by the higher salt content and thus plants cannot extract sufficient water from the soil to maintain growth.

As a general principle, when the depth to the water table is less than 1 m below ground level and certainly at a depth around 0.5 m (depending on soil properties), significant salinity will be evident on the soil surface. A line linking the red dots in Figure 6, suggests an evaporation rate between 10 and 100 mm/year is sufficient to initiate surface soil salinity.

When salinity is considered over the long term, landscape salinity is a transitory state for a catchment unless it has a non-draining lake or similar. Because a bare salted area is not stable, due to death of vegetation making it vulnerable to increased erosion, the catchment will try to come to a new equilibrium wherever possible by the excess groundwater leaching out the accumulated salts, eroding and draining the affected areas resulting in lowering the water table. Then revegetation with more salt and water tolerant species can occur once soil conditions become more favourable. The timeline for these changes to happen will generally be very long, 100s to 1 000s of years, reducing productive livelihoods in the meantime. In some situations, there are good warning signs and we can predict where salinity may occur and can minimise the extent of degradation.

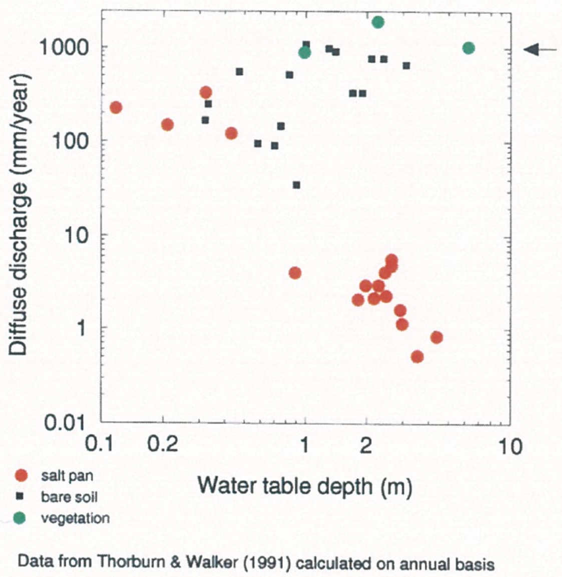

Figure 6. Removal of water (by evaporation and transpiration) from the soil with depth to the water table.

4. Forms of salinity

From the range of occurrences of salinity in Queensland, it is possible to identify readily identifiable landforms associated with the occurrence of salinity that align with the simple recharge, transmission, discharge model of Figure 2 and the restrictions to groundwater flow that lead to salinity. These were developed for Queensland by Shaw et al. (1987) and Salcon (1997). Figure 7 shows the common forms and readily observable features to identify catchments sensitive to salinity from likely restrictions to groundwater flow. Often more than one form of salting will occur together. For example, construction of dams, that can enhance recharge, and roads that compact the alluvium and restrict the limited water flow even further in sensitive landscapes.

The most common forms of salting in the Lockyer Valley, based on Figure 7, in decreasing order of frequency, are:

- catchment restriction - by weathering resistant Winwill conglomerate
- Confluence of streams
- Dams
- Roads
- Stratigraphic form

These are discussed in more detail in section 5

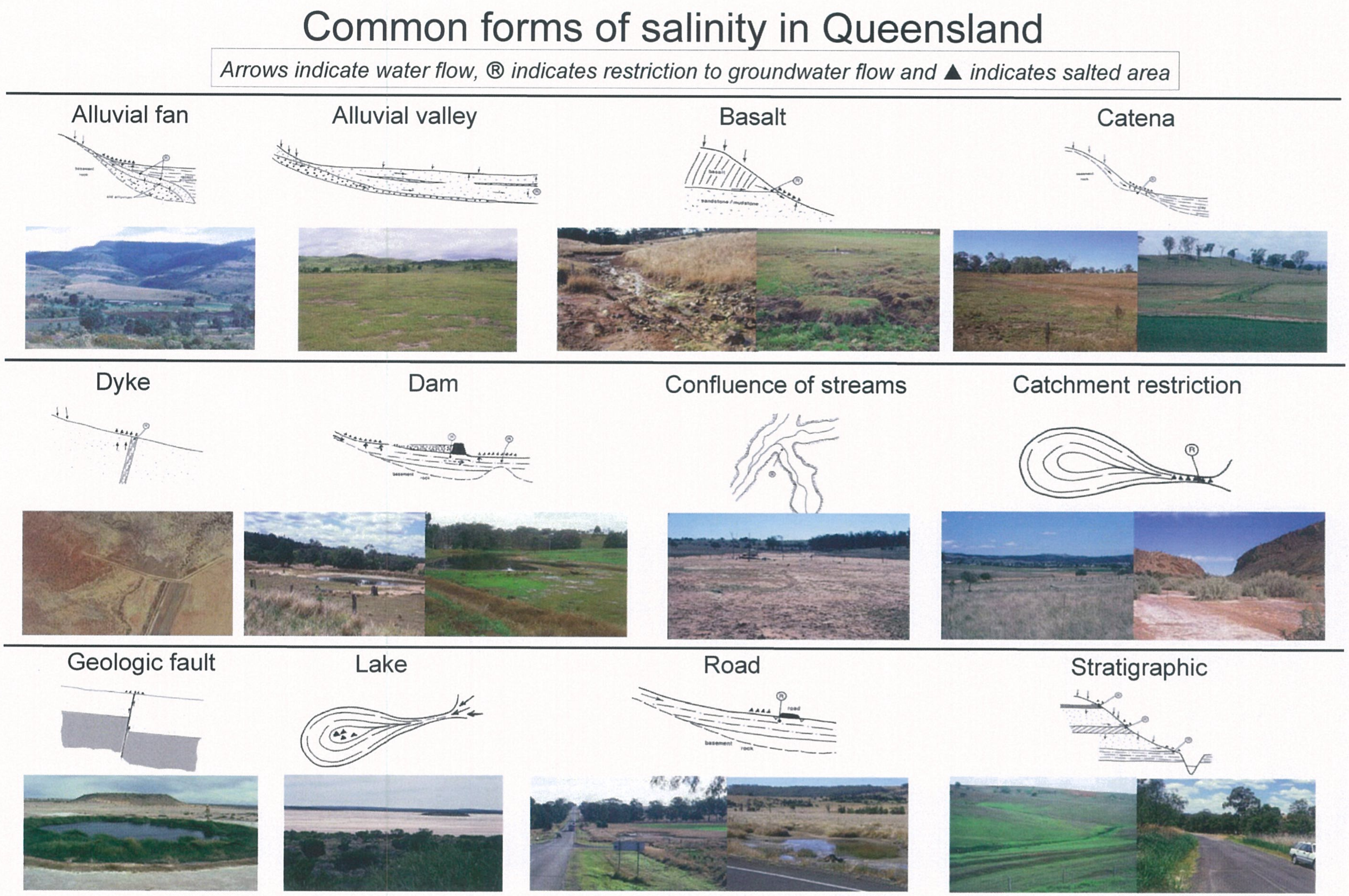

Figure 7. Common forms of salinity in Queensland identifying the restriction to groundwater flow and processes operating based on Shaw et al. (1987).

5. Landscape salinity in the Lockyer catchment

Considerable work has been carried out on salinity issues in the Lockyer catchment, in particular the southern tributaries from Laidley to Flagstone Creeks. Since Woolshed and Plain Creeks are part of the Lockyer catchment the processes operating in the rest of the Lockyer are likely to be applicable to these two catchments. Using validated processes from the rest of the Lockyer means a greater certainty for Woolshed and Plain Creeks to decide long term and sustainable management practices.

5.1 Location of landscape salinity

The map of salinity degradation for the Lockyer by John Shaw (1979) is overlaid on his Land Units map, which is essentially geology, indicating that salting occurrences present in the 1970s and into the 1980s are largely associated with the Winwill conglomerate formation as illustrated in Figure 8. The red areas in this figure indicate the location of salting not the relative size of the affected areas. While the Winwill conglomerate is now called part of the Koukandowie formation (Ellis et al. 2006), the characteristics and a possible similarity with Gatton Sandstone formation are particularly relevant to the occurrence of salinity, probably because of the resistance of the Winwill to weathering. For the purposes of this report, the older term of Winwill conglomerate will be retained because of the significance of its distinguishing characteristics.

5.2 Role of Winwill conglomerate formation

In the forms of salinity in Figure 7, the narrow throat of alluvium from the catchments with salinity is consistent with the catchment restriction form of salting restricting the rate of groundwater movement out of the catchment. Generally there is a very strong association with Black Tea tree, *Melaleuca bracteata,* vegetation in these areas (Photo 2) indicating the strong association with sensitive landscapes and waterlogging. In investigations in some of these sites with Black Tea tree and salinity, there is evidence through both calcium carbonate and iron and manganese concretions that they have been intermittently but strongly affected by salinity and/or waterlogging in the past. There are small occurrences of salinity in some of the smaller tributaries to the main southern tributaries of Lockyer Creek in the Ma Ma Sandstones and Walloon Coal Measures and while these are small they seem to be more associated with stratigraphic differences and local flows of water. Often Brigalow, *Acacia harpophylla,* is associated indicating both past and present areas of relatively high soil salt content.

If dryland salinity occurs in the Lockyer in catchments with restricted groundwater outlet as in Figure 8 and if Winwill causing a restriction to groundwater flow were true, this should also be reflected in the major southern tributaries draining into Lockyer Creek. Early work by Shaw and Gardner looked at these and in fact the salinity gradients with distance down the major southern tributaries indicated a similar effect moderated by the quantity and continuity of creek flow through the catchment and thus flushing of accumulated salts.

Figures 9 and 10 show the longitudinal transects of groundwater salinity from the bores in Ma Ma Creek and Sandy Creek as examples. Sandy Creek shows a pronounced restriction in alluvial width and depth near Blenheim and Ma Ma Creek shows extensive Winwill conglomerate as well as the stream junction with the stronger more consistently flowing Tenthill Creek. The higher bore salinity levels are associated with Winwill areas. All southern tributaries to Lockyer Creek do show areas of high salinity in the vicinity of the Winwill conglomerate exposure. Thus there is a very strong correlation between exposure of Winwill conglomerate and salinity.

Photo 2. Black Tea tree, *Melaleuca bracteata,* in a wet area of a western tributary to Sandy Creek, Lockyer Valley.

5.3 Role of Basalt geology

The area of basalt in each of the southern tributaries is related to the salt concentration in the groundwater since fractured basalt provides a source of good quality water which is released over an extended period of time. The tributaries with the largest areas of basalt have the lowest salt concentrations in the groundwater. The area of basalt in Woolshed and Plain Creeks is very low so that there is no continuity of good quality base flow in the creeks. Figure 11 gives the locations of the highest groundwater salt concentrations in the major southern tributaries to Lockyer Creek together with the locations of dryland salinity areas. This pattern confirms the significance of Winwill associated with salinity. Those southern tributaries with a high flow such as Tenthill and Laidley creeks show a lower salt concentration in the alluvial groundwater whereas those with lower flows, particularly Sandy Creek show a higher salt concentration at and upstream of the narrowest part of the catchment which is located in the Winwill formation. At these points the creeks are usually shallow and quite rocky indicating a restriction to groundwater flow out of the catchment. This occurs even though there is an incised stream at these places. The salt content in the alluvium and groundwater of these streams is probably still coming to a new equilibrium following lowering of sea levels after the alluvial deposition thousands of years ago. More recently, land clearing in the late 1800s and early 1900s and irrigation of the alluvia which commenced on a large scale in the 1940s are both slowly flushing salts from the unsaturated soil zone into the groundwater.

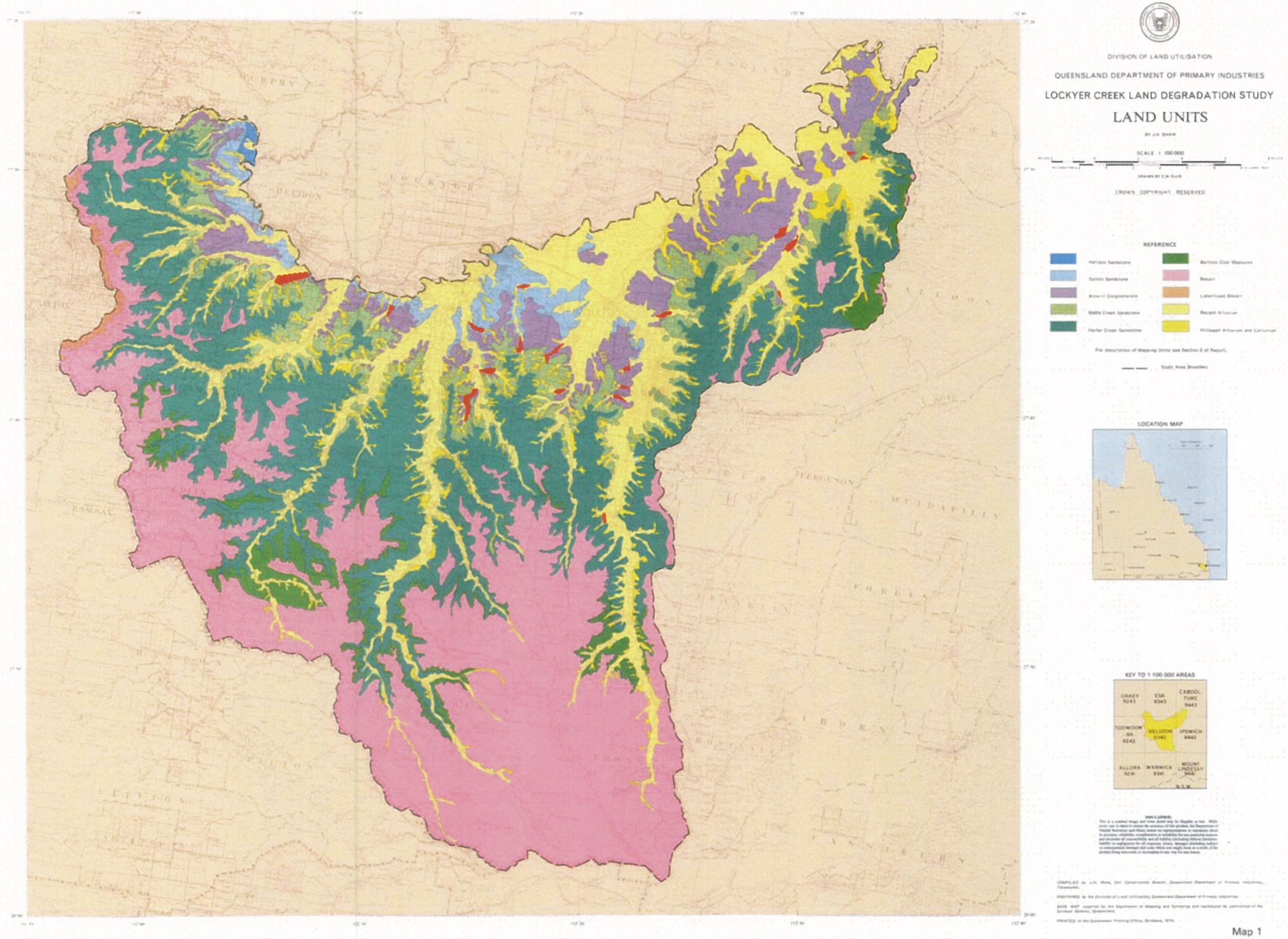

Figure 8. Dryland salinity in the Lockyer Valley as documented by Shaw (1979) shown as red areas with some additional sites added. The strong association with Winwill geology is evident. The areas of red are indicative of where salinity occurs and not an indication of the areal extent of salinity at each location. The base map is from Department of Natural Resources and Water.

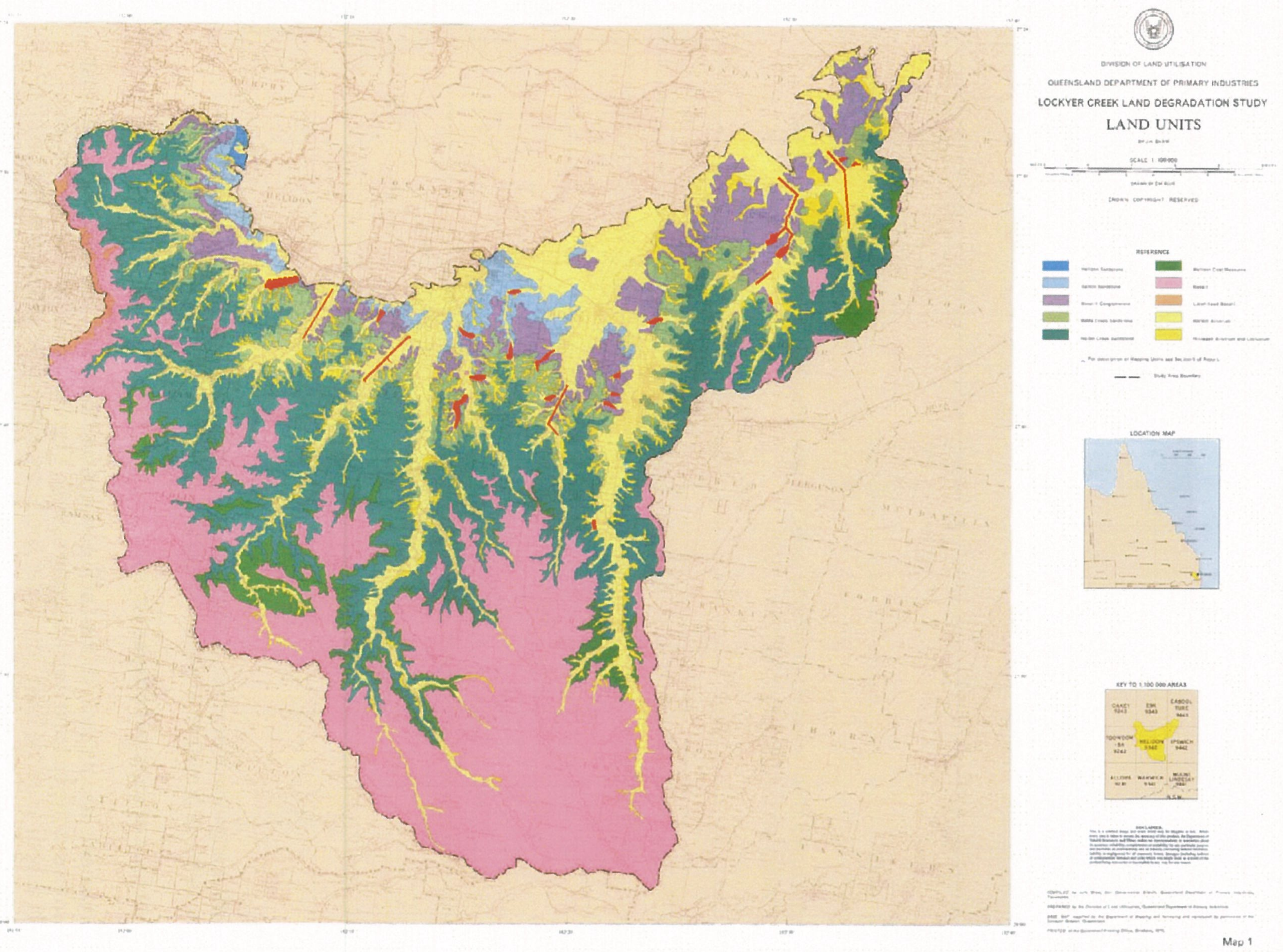

Figure 11. Regions of increased groundwater salinity in major southern tributaries (as indicated by the red lines) superimposed on Figure 8 illustrating the same close association with Winwill geology as for dryland salinity indicating similar salinity processes operating. The base map is from Department of Natural Resources and Water.

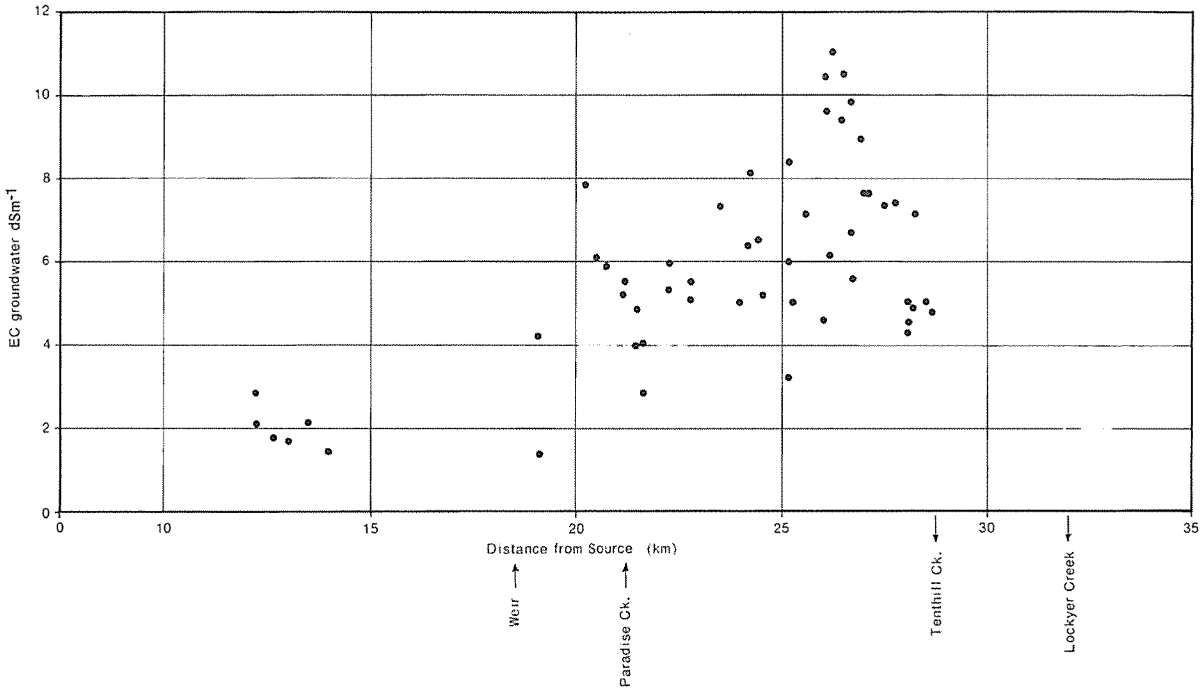

Figure 9. Longitudinal transect of salinity as EC of groundwater bores in Ma Ma creek, Lockyer Valley as published in Gardner (1985).

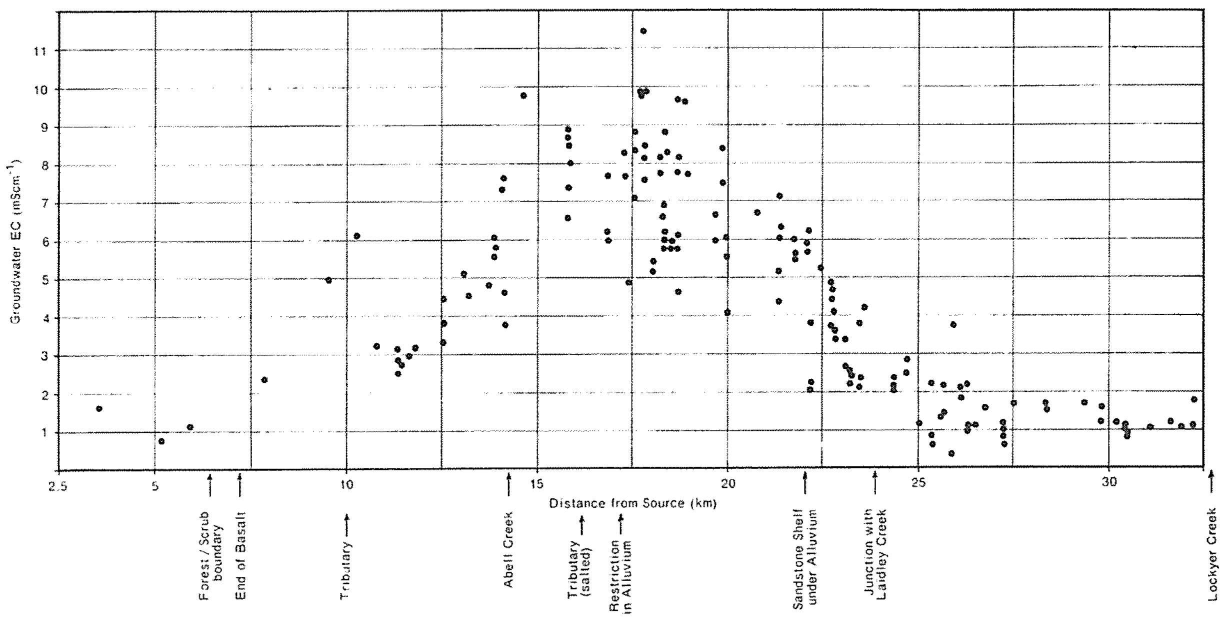

Figure 10. Longitudinal transect of salinity as EC of groundwater bores in Sandy Creek, Lockyer Valley as published in Gardner (1985).

5.4 Source of salts in Lockyer Valley

Early arguments about salinity in the Lockyer suggested that the Winwill conglomerate must be the source of the salt and water causing salinity. From all the available evidence, that does not appear to be the case. The water chemistry analyses as reported in Salcon (1997) page 95 to 97 clearly show that the salt composition in the alluvium reflects the composition of a basalt source which has been concentrated through evaporation. The evidence of the very low transmissivity of aquifers in Winwill formation as identified by Zahawi (1975) strongly supports the role of Winwill as a restriction to flow and not a source of salts and water for salt outbreaks. Table 3 shows the relative transmissivity expressed as cubic metres of flow per metre thickness of aquifer in the different geological formations taken from Zahawi (1975).

Table 3. Transmissivities of aquifers in the Marburg formation and in the alluvium in the Lockyer Valley from the data of Zahawi (1975).

Formation	**Transmissivity** m^3**/m thickness/day**
Marburg formation (upper beds)	11 to 103
Marburg formation (lower beds)*	0 -1.3 x 10^{-5} (< 0.000013)
Alluvium	75 – 1625

*The lower beds contain the Winwill conglomerate formation

The values in Table 3 indicate that it is most unlikely that the Winwill is a source of water because it has such low flow capability, but rather acts as a largely impermeable barrier to water movement.

A further reason that confirms the concentration of salts by evaporation rather than an additional source of salts is that a simple salt mass balance (salt inputs and salt outputs) for the catchment appears consistent with no major additional major source of salt to the catchment as demonstrated by Gardner (1985).The most consistent evidence is for the Winwill formation acting as a restriction to groundwater flow. This has also been confirmed for the adjacent Black Snake Creek catchment (Ellis et al., 2006). The very high groundwater salt concentrations (EC about 25 dS/m) at the bottom of the Woolshed and Plain Creek catchments are confirmation of the reduced flushing of the catchments. Gardner (1985) shows that the rate of flushing of salts out of restricted catchments such as Sandy Creek is very slow and will take a very long time to reduce as shown in Table 4. In the southern tributaries of Lockyer Creek with low salinity, the increased use of groundwater for irrigation reduces the flushing of salts out of the catchments resulting in a slight increase over time. Woolshed and Plain creeks were not evaluated in the work of Gardner but the processes operating in the major southern tributaries of Lockyer Creek appear consistent with the observed salinity in Woolshed and Plain creeks.

Table 4 Predicted future mean chloride concentration in the aquifers of the southern tributaries to Lockyer Creek from Gardner (1985).

Alluvial aquifer	Mean chloride concentration of groundwater (mg/L) for the years specified					
	1975	1980	1985	2000	2015	infinity
Laidley	165	165	166	166	166	170
Sandy	1 250	1 220	1 200	1 110	1 020	500
Tenthill	290	290	292	300	300	340
Ma Ma	1 720	1 740	1 660	1 440	1 200	350
Flagstone	820	840	800	715	640	175

6. Conceptual picture of salting processes in the Lockyer Valley

Figure 12 shows a three dimensional diagram of the salt processes associated with Winwill conglomerate geology and other forms of restriction to groundwater flow out of a catchment in the Lockyer valley. Under natural conditions salt accumulated at the bottom of the root zone as shown in Figure 3. If there was an intermittent shallow water table, then the salt accumulation would move upwards or downwards and show a profile shape similar to an intermittent discharge salt profile in Figure 3. As the water table rises further, vegetation would be killed and the historic salt moved to the soil surface and a bare salted area would result. If the water table rose to the soil surface and extensive seepage occurred, then much of the historic salt would be flushed from the soil. If on the other hand, local groundwater was used for irrigation, it would leach the accumulated historic salt down to the water table as shown in Figure 4. Thus the key issue in a salted catchment is being able to manage the water table level and salt load to minimise impacts over the longer term.

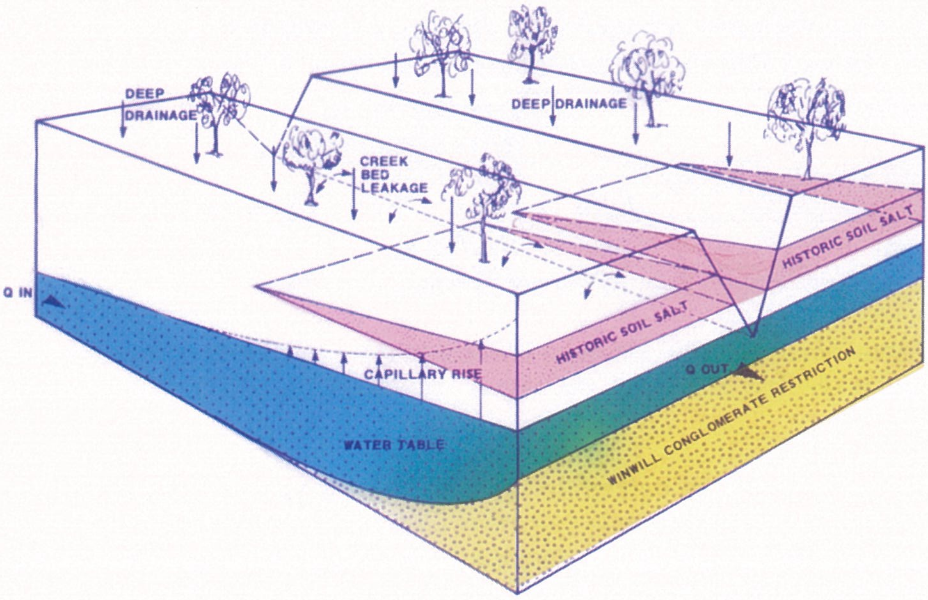

Figure 12. A three dimensional diagram of the salinity processes typical of a salted catchment and also the major southern tributaries in the Lockyer Valley from Gardner (1985).

In some of the salt affected small streams draining into the major southern tributaries of Lockyer Creek, dams were constructed in the past partly because the areas were wet and also because the narrow valleys and sometimes steep sides made them ideal locations to construct a dam. The presence of a dam has resulted in the equivalent of a 'hydraulic barrier' to water flow resulting in salting both upstream and downstream of the dam as a result of the leaking water filling all the available storage in the limited capacity alluvial materials. Figure 7 shows the processes and Figure 13 shows this effect for a dam near Mt Tarampa.

The dam has been in place for over 40 years. The figure shows that the area above the dam is saturated with surface salt accumulation from evaporation and below the dam the stream channel is also saturated and largely bare. This is occurring across the dark valley alluvium as well partly because the more restricted flow through this alluvium and the already high water table in the alluvium has meant there is no drainage outlet for the water. It is most likely that leaking dams have triggered the salting in other small sub-catchments. In the case of the example near Mt Tarampa, there is a relatively high proportion of Black Tea tree upslope of the dam indicating that this drainage line has always been sensitive to waterlogging which has been exacerbated by the dam. In other parts of the Lockyer, roads across wet lower parts of drainage lines have caused similar problems upstream by restricting even further the limited ability of water to flow through the alluvium by soil compaction. A classic example is Darbalara farm, University of Queensland near Laidley.

Figure 13. Example of the impact of a farm dam on salting in a drainage line in Winwill formation and the alluvium near Mt Tarampa in Plain Creek. The hydraulic barrier of the dam together with leakage has affected the upstream and downstream areas very significantly. Image from Google maps.

In summary, there is a distinct and repeating pattern of landscape salinity in the Lockyer Valley both in small dryland catchments and also in the major southern tributaries that shows that Winwill conglomerate geological formation is strongly associated with the occurrence of salinity. Figure 8 shows this association. Winwill formation is acting as a weathering resistant formation restricting the rate of ground water movement out of the catchments. Woolshed and Plain Creeks have an extensive occurrence of Winwill in the catchments particularly close to the junction with Lockyer Creek. This is consistent with the rest of the Lockyer catchment and also with the adjacent Black Snake Creek catchment. Thus a very similar pattern of salting is expected in Woolshed and Plain Creeks.

7. Factors modifying the expression of salinity

Two factors have a large effect in modifying the extent of salinity in a catchment given the other factors operating. They are hydraulic gradient and rainfall pattern.

7.1 Hydraulic gradient

The hydraulic gradient of the groundwater is an important factor influencing whether salinity will occur or not because it is the driving force for groundwater flow. This hydraulic gradient is closely related to the slope of the ground surface. Low slope situations are much more prone to show salinity.

7.2 Climate and rainfall patterns

Climate and rainfall patterns are important. South-western Australia has by far the worst salinity in Australia with Queensland relatively low. This is due to landform features strongly influenced by climate. SW Australia and Victoria have strong Mediterranean climates with winter rainfall during periods of low evaporation demand (usually < 1 mm/day) while NE Australia with a summer dominant rainfall has rain falling when there is strong evaporative demand (of around 5 mm per day). Thus in Queensland the opportunity for recharge is reduced except in very wet months with consistent rainfall.

Rainfall is the source of water for recharge. Thus rainfall patterns over time are important in the expression of salinity. Surface water irrigation, off stream storages and waste water disposal in non-sewered subdivisions can also be significant sources of increased recharge. Variations in rainfall patterns over periods of a few years tend to have a major influence on the expression of salinity. A moving average rainfall over a five year period is a simple and convenient way of showing rainfall variability. This is shown in Figure 14 for the DPI weather station at Gatton (040082) where the current very dry conditions are similar to the 1920s and thus the salinity visible currently is much less than would be present in average to wetter rainfall periods and salinity can be expected to increase considerably when wetter periods return. The rainfall trend appears to show both a short term pattern of variation with a periodicity of around 20 years and a longer term 80 to 90 year cycle based on the records available.

The bare salted area on Darbalara farm, University of Queensland, as assessed from air photographs appears to follow the rainfall pattern quite closely. Given that clearing appears to have happened in the late 1800s and early 1900s, there has been a relatively long lead time until a new equilibrium was established in the 1970s. This has coincided with a series of wetter years.

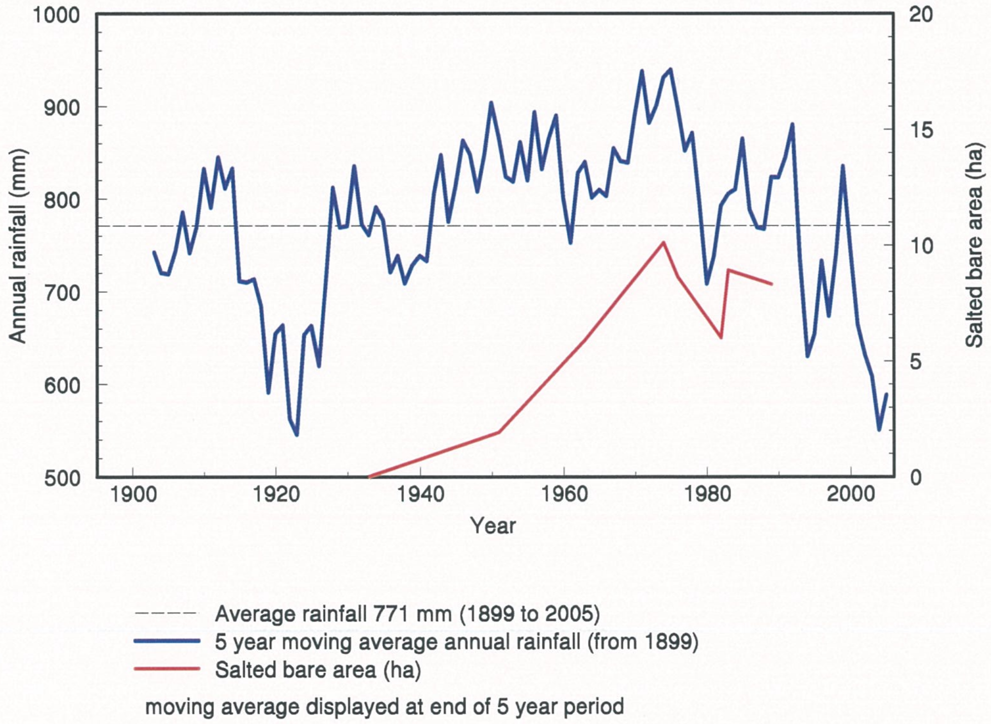

Figure 14. Moving average rainfall for DPI weather station (No 040082) near Gatton and the extent of bare salted area at Darbalara based on air photo interpretation. Rainfall data from Bureau of Meteorology and salted area from Department of Natural Resources.

As the rainfall decreased, the extent of bare area also decreased indicating that the system has come to a new quasi-equilibrium. The year the rainfall is plotted in Figure 14 is actually the average of the previous 4 years plus the year of the plotted value. The bare area is plotted in the year of the air photograph and thus the area of salting appears to react quickly to rainfall. While this is a reflection of how the results have been plotted it strongly confirms the effect of rainfall pattern on area of salting. Given the last several years have been particularly dry and salting is still very evident at Darbalara and many other places, the concept of reducing recharge by replanting vegetation and deep rooted perennial pastures will never be sufficient alone to reduce the area of salt affected land. It is a 'systematised illusion' whose veracity comes from constant repetition. Areas showing significant salinity in an extended dry period (such as the current period) when there has been little or no recharge indicates that more than revegetation alone will be required if salt affected lands are to be reclaimed.

8. Stages of salinity development and reclamation

The area of salinity in a catchment will increase until a new groundwater equilibrium is established where the quantity of water entering the groundwater through recharge is balanced by the quantity of water that:

- flows out of the catchment through the stream from groundwater or seepage, and
- is evaporated from the bare salted surface or any ponded area or wetland, and
- is transpired through the vegetation in the area where vegetation can use the groundwater. Areas where vegetation is effective usually have shallow water tables of less than 3 metres below ground and are largely non-saline (Hatton, 2002).

The time period for a catchment to come to a new equilibrium varies from a few years after clearing to 100 years or more depending on the catchment size, gradient of groundwater flow, rainfall, soils and sensitivity of the catchment to change in the groundwater balance. Many of the areas in Queensland that now show salinity have strong evidence of being at least temporally affected by salt in the past.

Salinity development and reclamation can be considered as stages in a process with recognisable features and management options for reclamation. Figure 15 illustrates the nine stages of salinity development and reclamation. Figure 16 shows some examples and photographs of what these stages might look like. Table 5 gives a description of the stages and outlines some broad management options to be considered. Site characteristics will determine the actual suitability of any one management approach and its long term viability. Some investigation and rough calculations of catchment groundwater and salt balances are usually required to make sure any investment in reclamation is effective for the longer term.

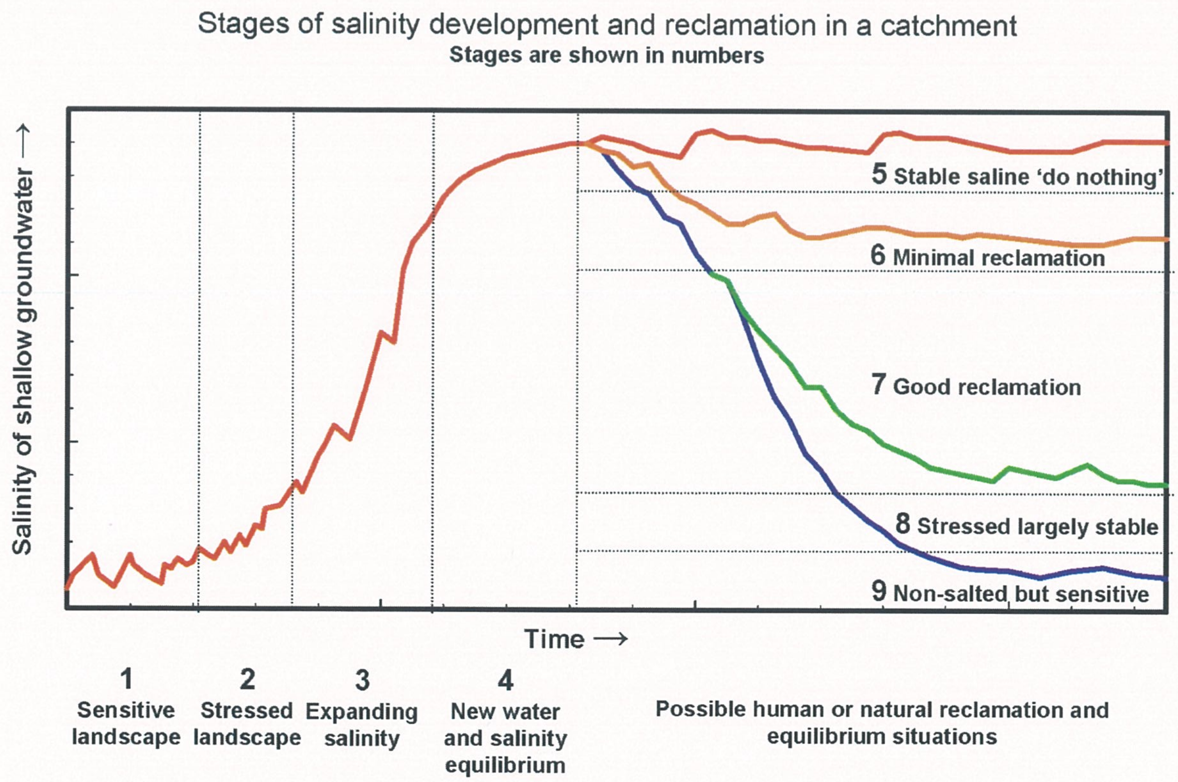

Figure 15. Stages of salinity development and reclamation. From Shaw (unpublished).

Stages 1 to 4 are stages of salinity development and stages 5 to 9 are stages of progressive reclamation, where it is possible. Some salted areas can reclaim themselves naturally and others can be easily reclaimed by human intervention but the majority are difficult to very difficult to reclaim depending on the geology of the area and the quantity of water that needs to be managed. The salinity of the groundwater at a depth of between 2 and 5 metres in, or very close to, the salt affected area is a relatively good indicator of the stage of salinity and together with the area affected by salinity can indicate how difficult it might be to manage or reclaim.

Based on personal observations of salted areas in the Lockyer Valley over the last 25 years and the trends for Darbalara farm as shown in Figure 14, many of the visible occurrences have reached equilibrium, that is stages 4 or 5 of Figure 15. Some areas have reached stages 6 and 7 although they have been assisted by the series of dry years and thus it is unlikely it is a sustainable change for the better. Because there are often many indicators for stages 2 and 3, proactive and early management can make a major difference rather than waiting until the catchment is degraded and then attempting to reclaim it as discussed in section 9.

Stages of salinity development and reclamation in a catchment

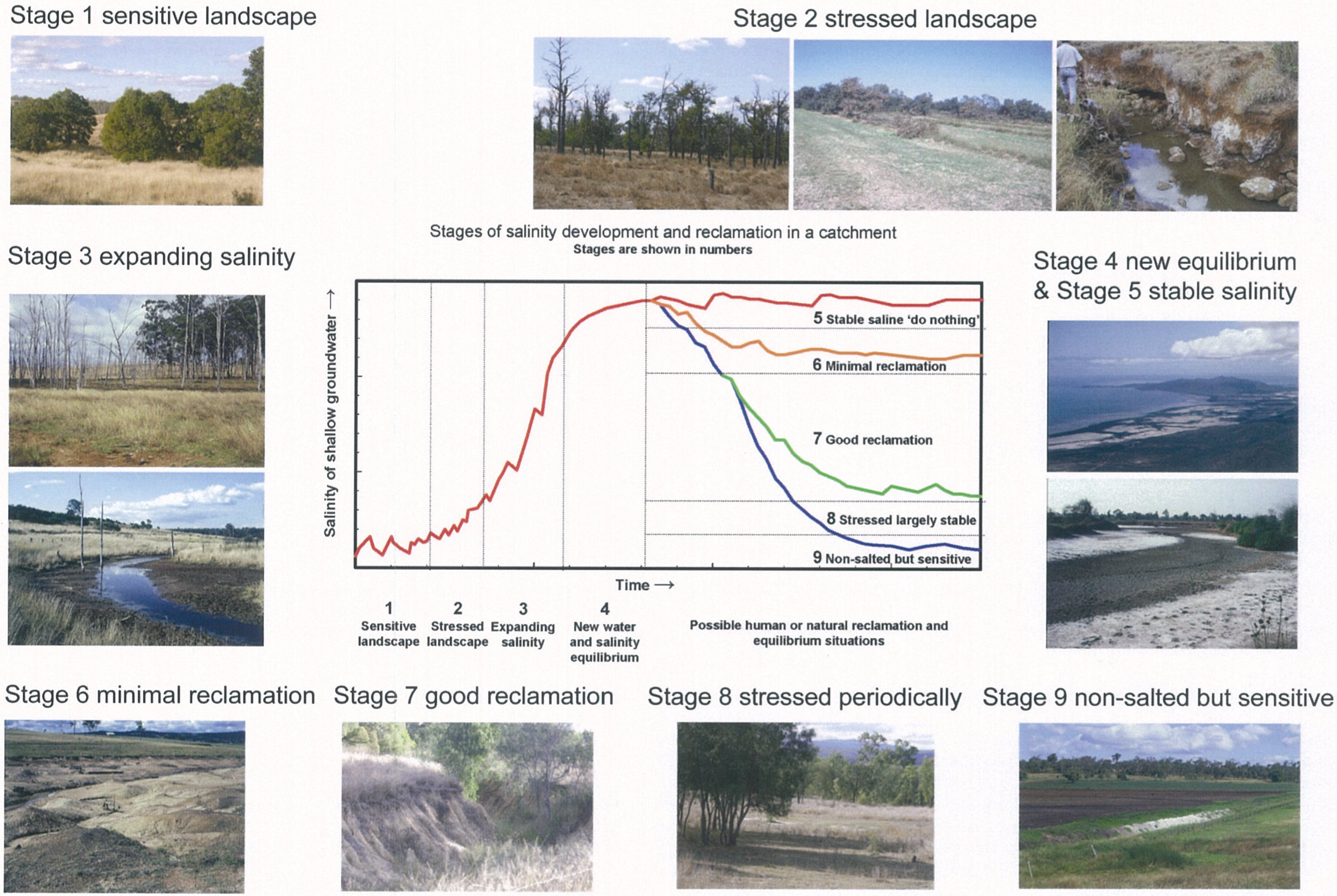

Figure 16. The nine stages of salinity development and reclamation with examples of each stage. Stages graph from Shaw (unpublished).

Table 5. Description of stage of salinity development and possible management options.

Stage	Name	Description	Management options
1	Sensitive landscape	Episodic seepage or saline bare areas of short time duration (< 5 years) but largely controlled by native vegetation which may be water and/or salt tolerant.	Proactive management and control measures are essential. Identify extent of episodically affected area, maintain native vegetation at all costs, minimise up stream catchment disturbance or preferably increase groundwater outputs in up stream areas to maintain the salt affected and adjacent areas intact.
2	Stressed landscape	Episodic bare, waterlogged and/or seepage area that lasts for longer than about 10 years. The extent of the affected area is responsive to varying rainfall. Affected area shows signs of tree death and change in grass species.	Proactive management and control measures are essential. Controlled grazing of the affected and adjacent areas to maintain substantial cover at all times. A cultivated area with invasive grasses or periodic waterlogging should not be cultivated. Sow deeper rooted plants and/or lucerne or equivalent into the grass depending on the groundwater salinity and depth. Reduce groundwater inputs and increase groundwater use above affected area wherever possible to maintain the water table level in the affected area to > 3.5 metres below ground wherever possible.
3	Expanding salinity	A rapid change with increasing seepage and/or bare areas as the catchment comes to a new hydrologic equilibrium.	The lag time from a significant hydrologic change in the catchment can be short or in the order of several decades so that any management may be very slow to have an impact. Site investigations are needed to assess the salt and water balances to allow appropriate management options to be devised. Suitable options will depend on the quantity of water excess, the salinity of the groundwater and the soil salt content.
4	New water and salinity equilibrium	The area has reached a new equilibrium where the extent of the bare area plus any seepage reflects the quantity of water that has to be evaporated or removed to be in an approximate equilibrium.	Because the area has reached some stability, the quantity of water to be controlled can be roughly estimated. Given the associated salt loads, strategies can be devised ranging from 'do nothing' through site stabilisation to site reclamation. A priority is to stabilise the area as much as possible by removing stock and cultivation from adjacent areas and ensuring vegetative cover at all times. The next steps will depend on site characteristics but strategies will need to increase groundwater use above the salted area.
5	Stable saline 'do nothing'	The geomorphology of the area will be the major determinant in what eventuates over the long term or what can be achieved. The extent of bare area and/or quantity of seepage will vary with rainfall patterns.	The aim should be to stabilise the area as much as possible to minimise erosion and subsoil exposure. This will probably be a default option in situations where the quantity of water to be managed, the salinity and/or the geomorphology provide major limitations to what reclamation strategies can be implemented.
6	Minimal reclamation	Bare saline areas are transitory (maybe over centuries depending on climate). Natural processes try to reclaim the area by erosion and drainage to enable vegetation to re-establish resulting in some stability. Minimal reclamation would be expected where the geomorphology prevents erosion and gully formation.	As above for stage 5 but more options are available to reduce the salted area with time. There may be a continuum between stage 5 and stage 6 with some sites fluctuating over time. Reducing groundwater inputs and in particular using excess groundwater upslope of the affected area wherever possible are preferred options. Groundwater use is subject to salinity chemical composition and accessibility of the water.
7	Good reclamation	Some sites will reclaim significantly if they were not affected in the historic past and the geomorphology is favourable, or they can be readily reclaimed by human intervention.	This is a desirable state and can happen naturally where the geomorphology is favourable to lowering the water table. It is important to create a buffer by lowering the water table below any critical level to minimise evaporation at the soil surface to cope with natural variability in water inputs.
8	Stressed but largely stable	A site that shows only intermittent bare and salted areas or seepage similar to strategy 2 above.	As for stage 7 above except that it may not be possible to lower the water table sufficiently for most of the time and thus some small areas will remain affected in most years.
9	Non-salted but sensitive	A site that has returned close to the original water balance through natural or human intervention but remains hydrologically sensitive.	This is an ideal state but is not often achieved due to land use change upstream of the affected area. With careful monitoring, such sites may be maintained in this state by ensuring water table levels in the affected and adjacent areas are below any critical depth to minimise evaporation at the soil surface.

9. Concept of equilibrium and resilience

The two concepts of equilibrium and resilience are important in evaluating the stages of salinity development and reclamation and in determining the most appropriate intervention for control or mitigation to achieve a sustainable outcome. ***Equilibrium*** can be defined as 'a dynamic state of balance between the action of forces that counteract each other'. Once land clearing and use of land and water resources occurred, the forces acting on the landscape also altered because of increased recharge, increased surface runoff and associated erosion and reduced buffering by vegetation of the periods of above average rainfall and shallow water tables. Thus there was a shift to a new equilibrium state quite different from the original native state.

Resilience can be defined as 'the capacity of an ecosystem to tolerate disturbance without collapsing into a different state that is controlled by a different set of processes'. Resilience is a reflection of the sensitivity of a catchment to groundwater hydrological change. There are four factors that have a major influence in determining the resilience of a catchment to development of salinity as given in Table 6.

Table 6. Key factors that strongly influence the resilience of a landscape to salinity.

Factor	Role	Situation for Woolshed and Plain Creeks
rainfall	groundwater recharge, surface flow & erosion	high probability of salinity at 800 mm. The approximate range for salinity is between 400 and 1300 mm/yr
rate of ground-water outflow	drainage and flushing of groundwater	very, very low
vegetation type and density	buffering capacity by variable density and accommodating wet periods	very low
relative sodium concentration	poor soil structure, poor permeability	very high

Factors such as hydraulic gradient, stream incision depth, salt load etc, also determine the resilience of a catchment to change in groundwater hydrology. Beyond a certain point, where water tables rise and surface soil salinity from capillary rise and evaporation causes the death of vegetation, the situation becomes unstable and the system will collapse to a less desirable state. This is equivalent to stage 3 of the stages in Figure 15.

The changes that occur are illustrated in Figure 17. As the degree of groundwater imbalance increases, salinity in the shallow water table areas increases until a critical soil salinity is reached when the catchment changes into a different state. The critical soil salinity level is the salt concentration at which most vegetation can no longer grow productively in an area. Figure 17 also shows the approximate stages of Figure 15 and Table 5 showing the points of transition to different states.

To restore a saline catchment means two changes at the same time are required:

- reduce soil salinity levels in the root zone to below the critical soil salinity value.
- reduce the degree of groundwater imbalance to lower the water table levels since water drives the system.

In general, a salted catchment will follow the upper curve of Figure 17 in reclamation down to the critical soil salinity level which will always be a value for the groundwater imbalance that is much less than when the catchments began to show salinity and flipped into the degraded state. The non-linear change means that considerable change in water and salt is required before vegetation can re-establish successfully. Planting salt tolerant vegetation into salted areas is only viable short term. Also Figure 17 indicates that just reducing groundwater recharge will not result in a change unless soil salt levels are also reduced. Because salted and bare areas often have changed soil structure due to the high sodium concentrations, leaching of salts is slow and soil dispersion makes plant establishment difficult as well. Thus once a catchment has reached stage 3 of Figure 15, it will be much more difficult to treat effectively.

Thus it is important to maintain a buffer depth to groundwater in catchments that are sensitive to salinity, that is, in catchments that have low resilience to be able to cope with rainfall and groundwater level fluctuations before the critical soil salinity value is reached. Monitoring the signs of stage 2 are vital to successful and sustainable management options.

Considerable areas of the alluvium of Woolshed and Plain Creek catchments are very close to the critical soil salinity threshold over extensive areas. Some areas have already exceeded the critical salinity threshold. Also the very high groundwater salinity levels over much of the catchments (EC around 25 dS/m) at only 3 to 4 m below ground currently, in a very dry period, indicate these catchments are very close to the tipping point where large salted areas are expected to develop. There are increased land development pressures on these catchments that could well tip the catchments into a degraded state that would be virtually impossible to reclaim given the quantities of water and salt involved.

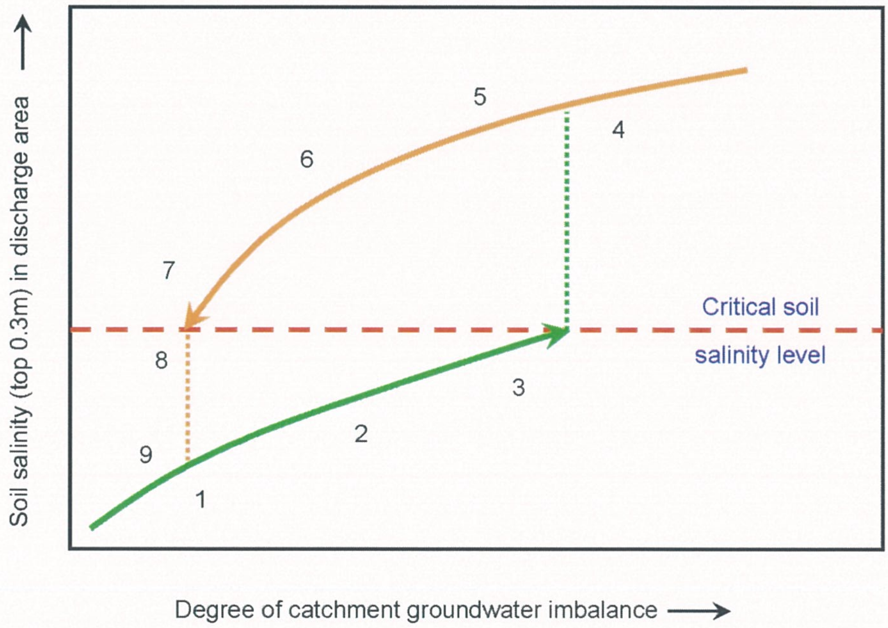

Figure 17. Change of state from a normal catchment to a degraded and saline catchment and the degree of reversal to restore the situation given the need to return below a critical soil salinity level. The numbers correspond approximately to the stages of salinity development and reclamation of Figure 15.

10. Salt mass balance

When there are high salinity levels in creeks, it is often assumed that there will be a large impact on receiving waters. This is only true if there is a reasonable flow rate of high salinity water. The concept of mass balance is important to put salinity into perspective. The salt load is the concentration of salt multiplied by the quantity of flow.

What salt load means is that a large quantity of low salinity water can have a higher salt load on receiving waters than a low flow of saline water. Since the mass balance is usually conserved unless salts precipitate, that is salts remain in solution, then we can use the expression

$$Q_i\, c_i = Q_o\, c_o$$

Where Q_i = quantity of input water (as recharge to groundwater)
c_i = concentration of input water (reaching the groundwater)
Q_o = quantity of output water (groundwater rising to the surface or seepage)
and c_o = concentration of output water (groundwater)

Thus annual rainfall (EC 0.03 dS/m) of 800 mm/yr (8 ML/ha) as rainfall input into the catchment can be in equilibrium with a drainage of salty water out of a catchment of EC 25 dS/m.
The salt mass balance approach is also applicable to stream flow in a catchment and is important in determining the impact a high salt concentration in stream water will have on downstream receiving waters. There is a simple but non-linear mixing relationship between the salt concentration of the base flow of a stream at very low flow and the salt concentration of stream at very high flow which can be roughly approximated by rainfall. Between these two extremes, the salt load out of a catchment is quite dependent on flow rate as illustrated in Figure 18 based on the McIntyre Brook, SW Queensland. There is a hysteresis effect where the first high flow is of higher salt concentration and the receding flow of lower concentration.

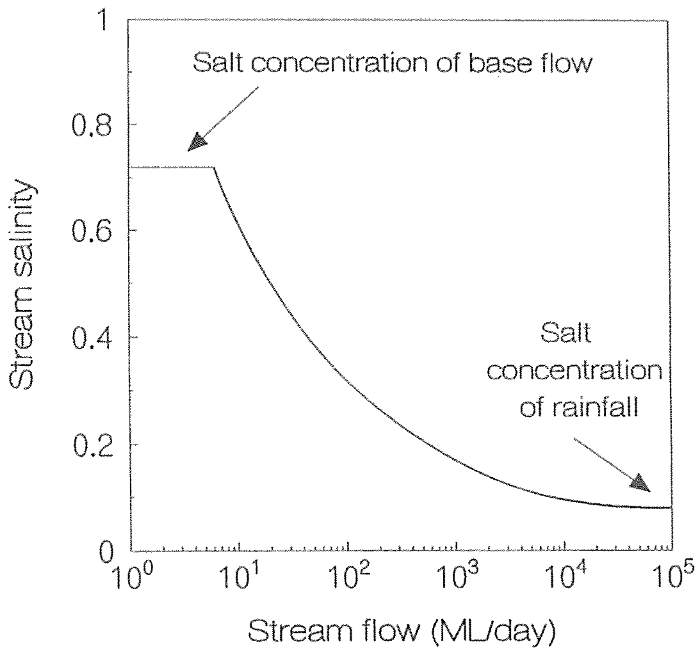

Figure 18. Conceptual mixing model of surface water flow between the extremes of base flow concentration and the concentration of rainfall at high flow.

Using this model and the relationship for Purga Creek in the nearby Bremer catchment because data was available, and substituting the EC for Woolshed Creek base flow at 25 dS/m instead of the EC of the base flow of Purga Creek at 7 dS/m reaching a value of EC 0.2 at a flow rate of 1000 ML/day allows a rough estimate of the salt mass balance for each of the creeks. Table 7 gives a very approximate example of the mass of salt moving out of the catchment at different creek flow rates. The table shows that the impact of the high salinity of the groundwater in Woolshed and Plain Creeks will probably only become a problem at moderate to high flow rates.

Table 7. Estimated mass of salt moving from Woolshed or Plain Creeks at different flow rates entering Lockyer Creek alluvium.

Surface flow (ML/day)	Estimated EC of stream flow (dS/m)	Mass of salt leaving the catchment (tonnes/day)
0.001 (1 000 L/day)	25	0.02
0.01	25	0.2
0.1	25	2
1	12	8
10	5	33
100	1.5	100
1 000 (1 billion L/day)	0.2	133

11. Salinity in Woolshed and Plain Creeks

Based on field trips in July and August 2006 in Woolshed and Plain Creeks and measurements of the salinity of creeks and watercourses where water was available suggests the pattern of salinity distribution and causes as seen for the rest of the Lockyer holds equally well in these two catchments. Figure 19 is a map of the catchments with measured water salinity values and also bore data from bores in the northern end of Plain Creek and in the adjacent Lockyer Creek from Department of Natural Resources and Water (Ashley Bleakley) and from the West Moreton Landcare group. Where other data was used, the latest date of sampling was used to represent the drier period of the last few years for consistency. The dates were within the range of November 2004 to July 2006. The data presented in the report of Whereat (1993) was consistent with the values and spatial trends in Figure 19.

There are large gaps in the data which could be improved from records and measurements of private bores and access to creeks on private property, particularly to the south of the Warrego highway to refine the spatial application of the most optimal strategies as suggested later in Section 13. Some additional information on the history of salinity development and major land use change would also be useful to ensure the strategies are appropriate. However overall, there is sufficient data to confirm the overall processes operating and the preferred strategies in each area of the two catchments as outlined in Section 13.

The very high EC at the bottom of the catchments in Figure 19 confirms the semi-closed basin nature of these creeks with very limited outflow due to a very restricted groundwater outlet at the northern end of the creeks from:

- weathering resistant Winwill conglomerate or similar geology restricting flow,
- the confluence of the creeks with the higher and more persistently flowing and greater alluvial deposition from Lockyer Creek.

The available bore logs for the bores drilled on Plain Creek from Department of Natural Resources and Water indicate an average aquifer thickness of just 0.75 m and a depth to the aquifer of between 3 and 6 metres. There is a very sharp contrast in depth of bores and salinity of the groundwater over a short distance between Woolshed and Plain Creeks and Lockyer Creek. Bores in Lockyer Creek are in the order of 20 m deep with EC typically less than 1 dS/m.

The standing water level in the bores in Plain Creek is shallower than the depth to the top of the aquifer indicating the groundwater is under upward hydraulic pressure of between 1 and 5 metres based on the small number of bores drilled. This is indicative of confined groundwater flow out of the system where the rate at which water can flow through the aquifer is less than the groundwater inputs. This is also consistent with the many evidences of saline bare soil areas as well as the leaking dam at Mt Tarampa, Figure 13. Thus the ability of the groundwater to move out of the catchment is confirmed to be severely limited. Secondly, a confined aquifer will respond quickly to changes in groundwater recharge and bare and seepage areas will develop quickly where there are easy flow paths for groundwater to move upwards to the soil surface. The problem is probably also caused by the sedimentation in the creeks resulting in some confinement of any exposed aquifers reducing the potential for excess water to flow into the bed of the creeks. This could worsen the situation and strongly suggests that the lower parts of the creeks are in advanced stage 3 (Figure 15) and salting could appear quickly unless some management interventions are commenced.

The situation south of the Warrego Highway is variable. Plain Creek shows small areas of salting and high salinity consistent with shallow water tables and small localised seepages. The two eastern tributaries of Woolshed Creek have small areas of shallow watertables and salting. Good water quality (EC around 0.5 dS/m) occurs on the eastern area of the alluvium. Most of the creek crossings visited in July and August 2006 were dry and a lot inaccessible so further data would be beneficial. The headwaters of the western tributary of Woolshed creek show high salinity and this is persistent in waterholes down to the junction with the other two tributaries of Woolshed Creek and based on landholder reports and creek analysis seems to influence Woolshed Creek at times. This is attributed to both a confluence of streams issue and to more prevalent small saline seepages in this area.

There is salting in Woolshed Creek just south of the Warrego highway and extensive salting to the north of the highway attributable directly to the restriction of Winwill conglomerate in this area and also to the generally high water tables following land development. Photo 3 shows Winwill formation in the base of Woolshed Creek. This salinity is a direct reflection of the shallow water tables caused by the general increased groundwater recharge in the catchment and also the underlying weathering resistant Winwill formation forcing the groundwater close to the soil surface. The western and eastern rural residential subdivisions on both sides of the catchments on the northern side of the Warrego highway show existing salting and what is expected to be increased salting once normal rainfall patterns return. This is due to the increased hydraulic loading from the reticulated water supply and on-site disposal on soils and landscapes that are very poorly permeable resulting in increased water inputs to the catchment. These areas are of major concern as discussed in Table 9.

The similarities and differences from the patterns in the rest of the Lockyer are summarised in Table 8. In general there are close similarities except that the degree of restriction to groundwater flow out of the catchment is considerably worse, the groundwater salinity is much higher and the extent and influence of Winwill geology is much greater.

Photo 3. Woolshed Creek and weathering resistant Winwill conglomerate formation just south of the Warrego Highway

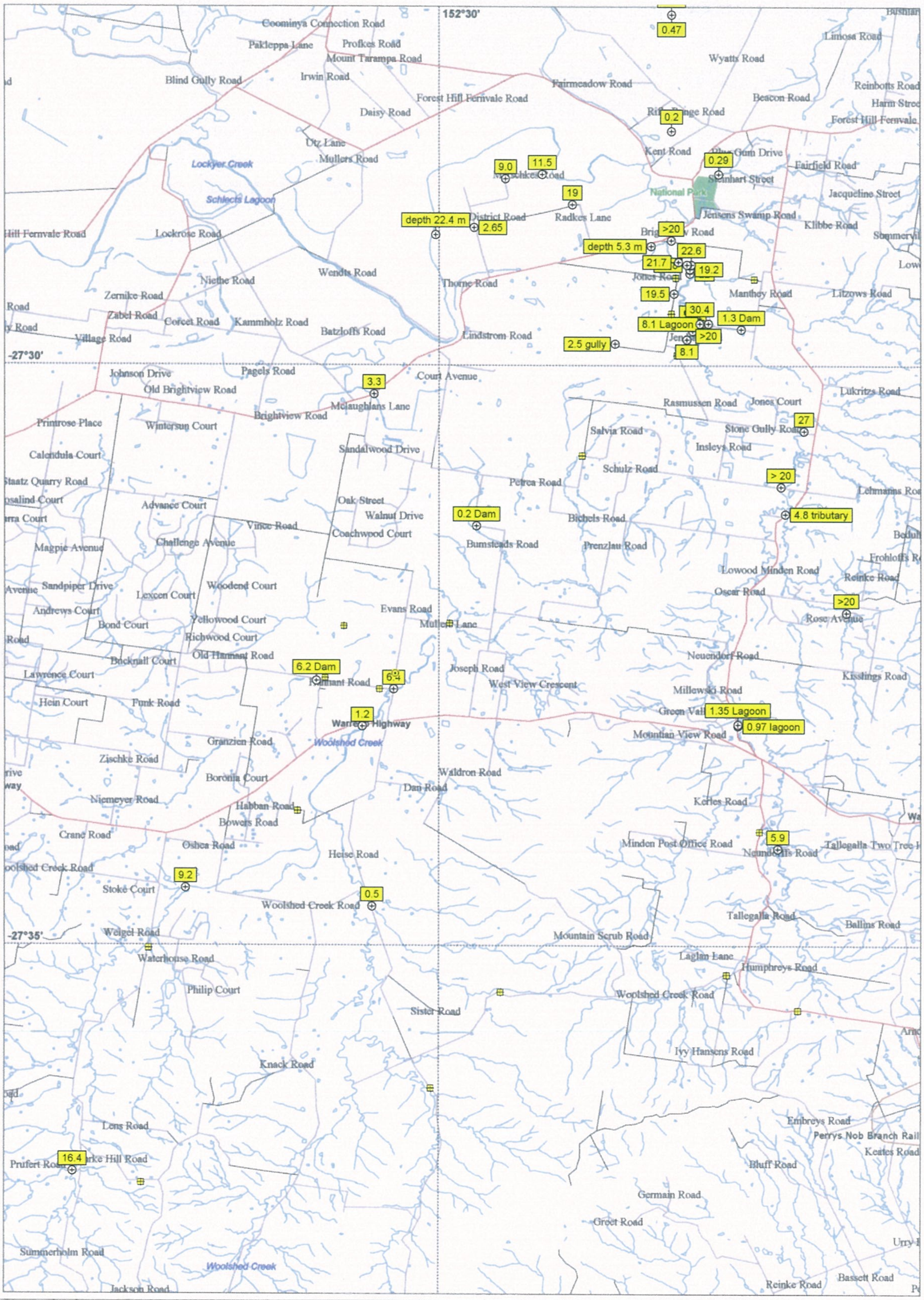

Figure 19. Measured EC of streams, dams and waterholes in Woolshed and Plain Creeks in July and August 2006, from bores at the downstream end of Plain Creek and from West Moreton Landcare group monitoring. The contrast in bore depth for selected bores in the downstream end of the creeks is also given. Base map from DiscoverAus.

Table 8. Similarities and differences in salinity in Woolshed and Plain Creeks in comparison to the southern tributaries of the Lockyer Valley and the expected implications.

Woolshed /Plain creeks	Lockyer – major southern tributaries	Likely impacts
More extensive exposure of Winwill, particularly in northern end of the catchments.		Greater restriction of water flow out of the catchments and less defined stream channels mean shallower groundwater, greater risk of saline areas developing and limited opportunities for natural drainage of groundwater out of the catchment. Catchments act as semi-closed basins where salts accumulate over time by evaporation and transpiration with only periodic flushing of a small portion of the groundwater.
Extent of basalt geology providing a source of good quality water and persistent stream flows is very limited. The main streams are very limited and show extensive silting so that there is limited discharge of saline water out of the catchments.	Extensive depth and area of Basalt in headwaters. Catchments with greater basalt have base flows of good quality water for longer periods resulting in greater flushing of catchments.	Salts will be concentrated and not flushed from the catchment. This is confirmed by the high groundwater salinity in the northern ends of the catchment.
Confluence of streams at the junction with Lockyer Creek reducing groundwater flow capacity out of the catchments substantially.	Confluence of streams does occur but is substantially less because of more consistent base flow in the southern tributaries and in Lockyer Creek enhancing its flow downstream and associated deposition of alluvium at the junction with Woolshed and Plain Creeks.	Salt loads and excess groundwater will be very difficult to move out of the catchment from normal stream channel processes. Thus catchments are at considerable risk from changes in hydrological regime and increased development pressures such as the extent of non-sewered subdivisions and of dams.
A greater incidence of small seepages in the upper Marburg beds in the upstream sections of the creeks.	Generally less frequent outbreaks.	These are expected to have only a small impact because of their limited size and generally low flow. They probably result from a greater diversity of permeable and less permeable beds in this geological formation than for the rest of the Lockyer and the smaller base flow from basalt. The western tributary to Woolshed Creek south of the highway is of concern.
Salting of narrow streams through Winwill that join the major creek alluviums.	Very similar to Woolshed/Plain creeks.	Small and localised areas mean there is some opportunity to manage them but where increased inputs from non-

Woolshed /Plain creeks	Lockyer – major southern tributaries	Likely impacts
		sewered subdivisions occur, the additional hydraulic loading will be significant in salinity outbreaks and also affecting nearby alluvium.
Depth to very saline >20 dS/m) groundwater in northern areas of the alluvium areas is shallow, less than 3 to 4 m, and extends up the creeks for several kilometres.	Groundwaters generally much less saline (< 8 dS/m) and are at a deeper depth below ground level partly due to irrigation in the southern tributaries.	This is a major salinity risk for the Woolshed/Plain Creek catchments as increased groundwater recharge will cause the watertable to rise within the capillary rise distance of the soil surface and cause major salting. Figure 5 illustrates the processes and the likely effect is expected to be much worse given that the salinity of the groundwater is > 20 dS/m. Figure 17 shows the change of state expected for the northern sections should the water table levels rise to less than 1 metre below ground and remain high.

The pattern of confluence with streams resulting in high levels of salinity due to restricted groundwater outflow and shallower watertables is a consistent pattern in many major river valleys. Both Flagstone and Ma Ma Creeks in the Lockyer show the pattern to a lesser extent. The Callide Valley system near Biloela and Dululu as shown in Figure 20 shows the salinity transect and also the transmissivity changes in the lower Dee River where it joins Callide Creek. The pattern of salinity found for the Callide by Dowling and Gardner (1988) indicates a very similar pattern to the stream patterns for the southern tributaries of the Lockyer where restricted outlet and evapotranspiration result in concentration of salts down the alluvium. The salinity at the junction of Woolshed and Plain Creeks with Lockyer Creek is at least twice as high as other systems in Queensland and thus of major concern.

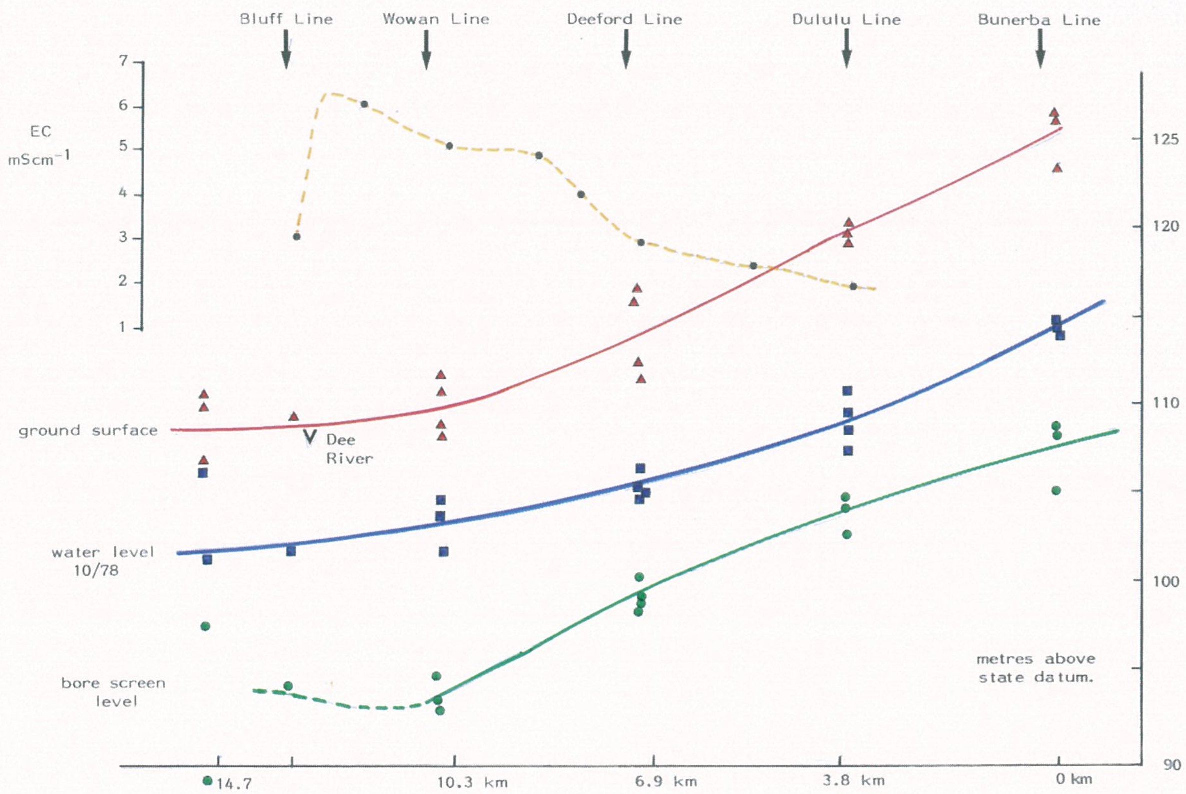

Figure 20. Longitudinal transect through Dee River valley to the junction with the Callide. The transmissivity of the aquifer in the Wowan line was 1 100m^3/m/day and for the Bluff line near the confluence with Callide Creek was 180 m^3/m/day. Data plotted from Queensland Water Resources Commission reports.

11.1 Emerging trends and pressures in Woolshed and Plain Creeks

There are four emerging trends that are expected to make salinity issues considerably worse in Woolshed and Plain creeks in the short and longer term.

1. *Rainfall expected to increase* Major areas of salting and shallow water tables are present in both creeks now following a period of 10 to 15 years of decreasing rainfall indicates that in a wetter rainfall period, salting will increase. Figure 14 suggests the possibility of an increase in rainfall should the pattern for the last 100 years be repeated as seems likely. The severity of salting will depend on the rainfall increase as the dominant factor affecting future change. Given the dry conditions, any strategy that mimics reduced recharge as a management strategy will be inadequate to manage salinity in the catchments.
2. *Non-sewered residential subdivisions*. Since these areas receive reticulated water supply and collect and store rainwater, which is then used and disposed on-site, there is a large additional hydraulic loading from the developments. The work of Ted Gardner (pers comm.) indicates that the water use in non-sewered developments is in the order of 150 to 200 litres per person per day. Assuming 160L/person/day and given four people per house on 0.5 hectare blocks, and that only about 1/3 of the water is evapotranspired due to over wetting by the disposal systems, then this will amount to an increase of some 154 000 L/block/year. This is equivalent to additional rainfall of 300 mm/yr/hectare of residential area. Waterlogging, wet areas and salinity issues have already occurred and will only get considerably worse in wet periods. Photo 4 shows water flow paths around Rose Avenue indicating this is already occurring. A very similar pattern is also evident in the western sub divisions. Since the soils on this geology are sodic and relatively impermeable, surface flows and salinity as well as possible nutrient issues are likely. In the middle upper section where Rose

Avenue crosses the creek there is salting with a creek salinity of EC >20 dS/m. Many of these subdivisions seem to be developing on Winwill conglomerate which can only make the salinity issues much worse and also result in small drainage lines out of Winwill becoming permanent flows with potential for algal blooms etc depending on how well the disposal systems are maintained and functioning. Gardner et al. (1995) concluded that the commonly accepted disposal area for on-site disposal was far too small to ensure the supply rate of effluent matches the rate of water use of the vegetation in the disposal area. Gardner et al. (2005) found that shallow water tables under septic trenches seriously compromised the efficiency and effectiveness of septic systems and also there was a high incidence of grey water runoff in audited areas confirming that future problems are highly likely to occur.

3. *Dams and storages on surrounding Winwill formation* seem to leak and fill up the unsaturated storage of the drainage line. This is made worse if the dam is close to the heavy clay alluvium which has shallow water tables as shown in Figure 13. Because the salinity of the main creeks is greater than can be used for agriculture, and because of periods of lower rainfall, dams and off stream storages will increase. These storages also reduce surface flows in the main streams, flushing of salt out of the catchment and maintenance of creek beds. They also reduce recharge of the alluvial aquifers resulting in less flushing of salts present in the main creeks which will result in a steady but slow increase in salinity of the system.
4. *Degree of sedimentation in creeks and degradation of riparian vegetation* The degree of sedimentation in creeks is expected to restrict drainage of groundwater from the shallow water table areas by the creeks and the confinement by the sedimentation is pressurising the saline groundwater so that it now covers a larger area of the catchments. Sedimentation in the creeks was reported from landholder surveys by Hogan (1996). It is quite probable that this will cause shallower water tables further and further upstream because of groundwater confinement. Photos 5 and 6 illustrate the current state of Plain Creek near the Warrego Highway and near the northern end respectively indicating significant degradation.

Photo 4. Evidence of surface flow from subdivision on Rose Avenue on the east side of Plain Creek. Image from Google maps.

Given these trends it is not possible for Woolshed and Plain Creek catchments to be able to cope with the increasing pressures. The catchments are essentially semi-closed basins with existing very high salt loads and shallow water tables being pushed to hydraulic overload.

They are at the point of tipping into a more degraded state (Figure 17) on a large scale unless proactive action is taken in the short term.

Photo 5. Poor condition of Plain Creek north of the Warrego Highway.

Photo 6. Sedimentation in Plain creek near the junction with Lockyer creek alluvium

12. Options to manage salinity

The following seven options cover the ways in which salinity can be managed. Often a single option is not sufficient of itself and combinations of options are required. These are each described in broad detail followed by specific comments in relation to Woolshed and Plain Creeks. Other options may be possible that I am not aware of. It is important to consider any options on a catchment scale rather than just on an individual site basis since the processes are often linked and upstream actions affect downstream impacts. The options are:

1. Do nothing
2. Stabilise the affected area
3. Reduce groundwater inputs (recharge area)
4. Intercept groundwater (transmission zone)
5. Increase groundwater outputs (discharge area)
6. Store the salt
7. Remove the salt

12.1 Do nothing

This strategy is appropriate for stages 1, 5 and 8 of Figure 15 depending on other conditions. It is most applicable to situations where:

- The salinity situation is relatively stable
- Bare salted areas are intermittent or small
- The saline base flow from the salinity affected area is relatively small in quantity with minimal salt load impact on downstream resources. A rough catchment water and salt mass balance may be needed if there is a reasonable flow rate to be able to make an appropriate judgement.

The preferred approach is:

- 'Fence and forget'
- Revegetate where cost effective and viable
- If it is an area of Black Tea tree or Brigalow or other indicators of wetness or salinity as past or present vegetation, these areas need to be substantially protected and vegetation increased in association with other methods to achieve a buffer depth to the water table to moderate water table levels in wetter periods to prevent spread of salinity.

12.2 Stabilise

This strategy is appropriate to stages 1, 2, 5, 6, 8 and 9 of Figure 15 if other factors are suitable. To have any chance of long term stabilisation of salinity, the soil salt levels in the upper root zone need to be reduced to below the critical soil salinity threshold level (Figure 17) where they have exceeded it and prevent an increase where they haven't. This means changing the groundwater imbalance of the whole catchment at the same time to reduce recharge. While revegetation of recharge areas is possible and will contribute, it will not be sufficient of itself. Strategies that use available groundwater where the quality is acceptable and reduce salts in the upper soil profile to below the critical soil salinity level at the same time will be required.

It is possible to overcome some of the soil salinity issues and commence the process by using mounded areas on the edges of salted areas as shown in Figure 21 and described in Table 9 in more detail.

12.3. Reduce groundwater inputs (recharge area)

This option is most appropriate to stages 2 and 8 of Figure 15 if other factors are suitable including a recharge area with a higher rate of recharge is identifiable and can be managed. However,

- Recharge areas are usually large and diffuse
- There are usually very long lead times for change. If it takes 70 to 100 years for salinity to develop and come to a new equilibrium then it will take at least that long by revegetation of much of the area for it to possibly reduce to a near normal level given normal rainfall. In cases where additional water is stored and or used in a catchment, there may not be adequate change in hydrology from revegetation alone to make any impact. Also, if a catchment is sensitive to hydrology and salinity under natural conditions, partial revegetation of recharge areas will still be insufficient.
- The option may be useful in combination with other strategies such as using all available groundwater in the upper part of the catchment above any major salinity area.
- There are many good reasons for revegetating a catchment, but salinity is not a sufficient reason of itself and it is most unlikely that revegetation alone will make a major impact on salinity.

12.4 Intercept groundwater (transmission zone)

This option is most appropriate for stage 2 and 3 with potential in stages 4 to 8 of Figure 15. It works best where:

- There is an identifiable transmission zone with reasonable flow rates, often alluvial channels, or side slopes of more permeable materials before they reach the less permeable alluvial areas.
- The quality of intercepted water needs to be suitable for the intended use. Irrigation is most effective since it can use large quantities of water and the area and crop to be irrigated can be matched to the available supply and water quality. For the Lockyer and surrounding areas, irrigation can effectively use about 4 ML/year/ha without causing other problems.
- The process is effective if water can be extracted upstream of a restriction where it is likely to be of better quality and can very effectively lower the water table in the affected area. Given that the porosity of soils with shallow water tables is in the order of 5 to 10% (maximum), removal of 1ML/ha of high water tables should lower the water table over 1 ha by 1 to 2 metres (where there is no lateral inflow). Thus pumping and using groundwater is very effective in lowering watertables.
- Evaporation basins also are relatively effective depending on salt concentration and leakage rates but require setting aside unproductive areas in the catchment.

12.5 Increase groundwater outputs (discharge area)

This option is appropriate for stages 2 to 8 of Figure 15 depending on other factors. In general:

- Vegetation is not very successful unless there is low salt content (below the critical soil salinity threshold) and a buffer depth to the water table of at least 0.5 m and preferably 1 metre is possible.
- Pumping is possible but generally the flow rates are low and linked tube wells may be required. In some discharge areas, flow rates may be so low that this is not effective.
- Drainage is effective if there is some more permeable material at depth and it can break through the restriction to groundwater flow. The salt content and flow rates need to be acceptable to downstream users to minimise impacts.
- Pumping and disposal in an evaporation basin is possible if the salinity level is too high for other productive uses.

One option is to allow salt flushing out of the catchment in periods of high flows since there is such a dilution effect as salt leaves the catchment. Figure 18 and Table 7 illustrate this point. A salinity trading system operates on this basis in the Hunter Valley NSW.

12.6 Store the salt

Use available groundwater above the Winwill restrictions with an EC of up to 6 to 8 dS/m by irrigating crops, trees or pastures where feasible. Since flow rates will be small, linked tube wells can be used or interception trenches if aquifers are shallow. Use of the pumped water on adjacent pasture or Rhodes grass or other acceptable salt tolerant grass vegetation is possible including on salt affected areas. Salt tolerant grasses are necessary as well as trees to stabilise the affected area.

Since it is important to reduce soil salinity at the soil surface and in the root zone of plants to less than the critical soil salinity level, then mounds are a possible method as illustrated in Figure 21. Place mounds about 0.5 m high and 1 to 2 m wide in longitudinal rows on the salted area beginning nearest to the salted margins and vegetate with salt tolerant grasses and trees and irrigate with water from upstream to move salt downwards in the soil profile and plant vegetation. Cracker dust or alternative material seems to work well providing nutrients and also good leaching of salt that may accumulate. Protection against erosion of upstream leading edges will be required. Once creeping or stoloniferous grasses establish, the stability of side banks would increase. This approach will have two effects;

- providing some productivity from the salted land, flushing surface accumulated salts below the active root zone depth and thus allowing a range of native vegetation to re-establish and
- lowering of the water table at the same time because it will use water at a faster rate than evaporation from a bare soils or salted area.

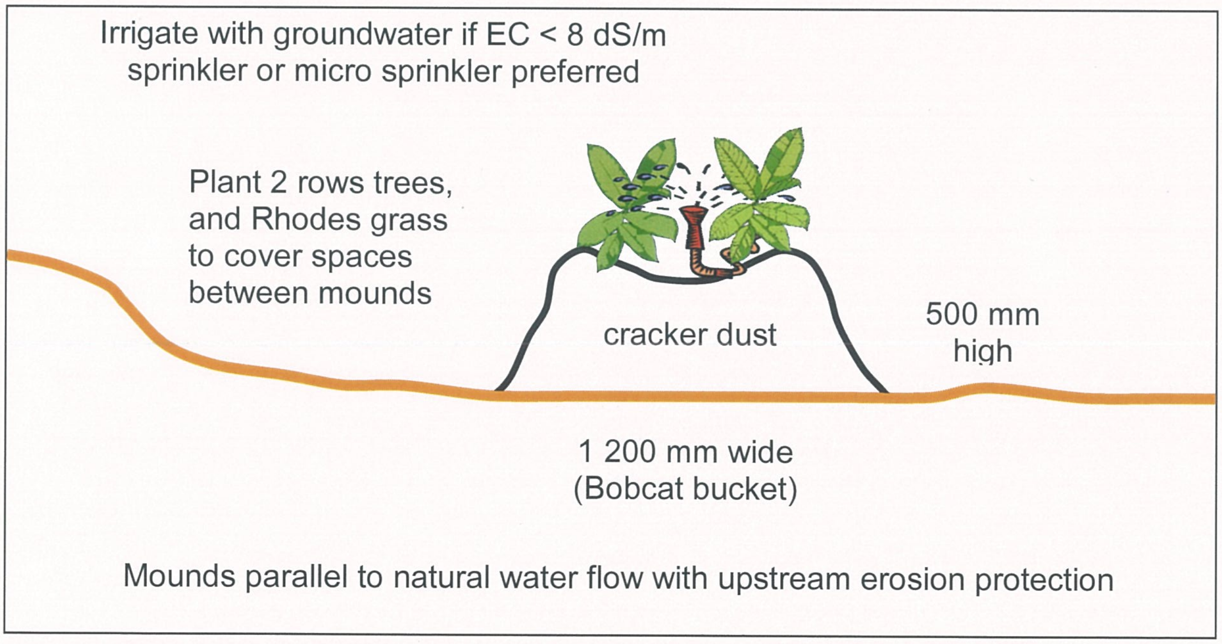

Figure 21. Structure of mounds to place near the edges of salted and bare areas to allow reclamation to occur. Irrigation is optional but desirable.

Sprinkler or micro-sprinker irrigation is much preferred to dripper systems as they provide a wider area for downward flushing of salts and do not generate the surface and lateral salinity concentrations at the edge of the wetted area that drippers do. Surface salt accumulation can result in death of vegetation following rainfall where the surface accumulated salts are washed into the root zone of the plants.

Once stability is achieved, it is critical to manage the depth to the water table to be at least 1 m below ground level and preferably 2 m or greater otherwise there is insufficient buffer should a particularly wet rainfall period occur. Once evaporation of salts on the soil surface recurs, the process needs to be recommenced.

12.7 Remove the salt

Where the salinity of the groundwater is as high as the bottom end of Woolshed and Plain Creeks, the only viable option is to remove the salt by flood flow release, transport of evaporated salt, by reverse osmosis techniques or solar distillation processes. Harvesting some of the salt from an evaporation basin and removing it from the catchment is the most cost effective option. This may mean an evaporation basin or where available area is an issue, or no above ground storage is feasible because of hydraulic barriers exacerbating the issues then a vertical 'evaporation tree' is possible using solar heating of the water and pumping and recycling of more concentrated waters. Designs need to maximise surface area for evaporation but have replaceable non-corrosive piping to overcome salt precipitation.

In some situations it may be possible to initiate an evaporation basin for a short period as a preventative control measure and remove a significant amount of water and salt while other measures are implemented in the catchment to bring it into a hydrologic balance.

13. Options and priorities for areas of Woolshed and Plain Creek catchments

A map of the stages of salinity development and reclamation for Woolshed and Plain Creeks based on the available data, field inspections and the emerging trends as identified in section 11.1 is given in Figure 22. The interpretation of stage of salinity development is based on Figure 15 and Table 4. The map area numbers in Figure 22 are referred to in Table 9 and the stages are an indication of the stage of salinity development and the potential salinity risk for the catchment. The colours of the shaded areas on the map in Figure 22 are:

Stage 1	sensitive landscape	not shown on map
Stage 2	stressed landscape	blue hatched area
Stage 3	expanding salinity	red hatched area (areas numbered 3+ are considered at greater risk)
Stage 4	new equilibrium	light brown hatched area
Stage 5	stable area	light brown hatched area (as for stage 4)
Stages 6 to 9	various reclamation	not shown as no areas found

The numbering of areas on Figure 22 commences at the most northerly end as this is the area of greatest likely degradation from salinity and progresses upstream for both creeks. The upstream areas contribute to the overall salinity risk as well as having specific risks in each section. Thus actions are required for all identified areas if the salinity issue in the catchments is to be managed sustainably. Table 9 outlines the recommended management options. The priorities for action are given in section 14. The indicated areas in Figure 22 are approximate at this stage and can be refined from consultations and historical information. However, they are adequate for planning and scoping of components of a salinity management strategy. Further investigations are required to confirm some of these conclusions and refine the parameters and estimates before implementation.

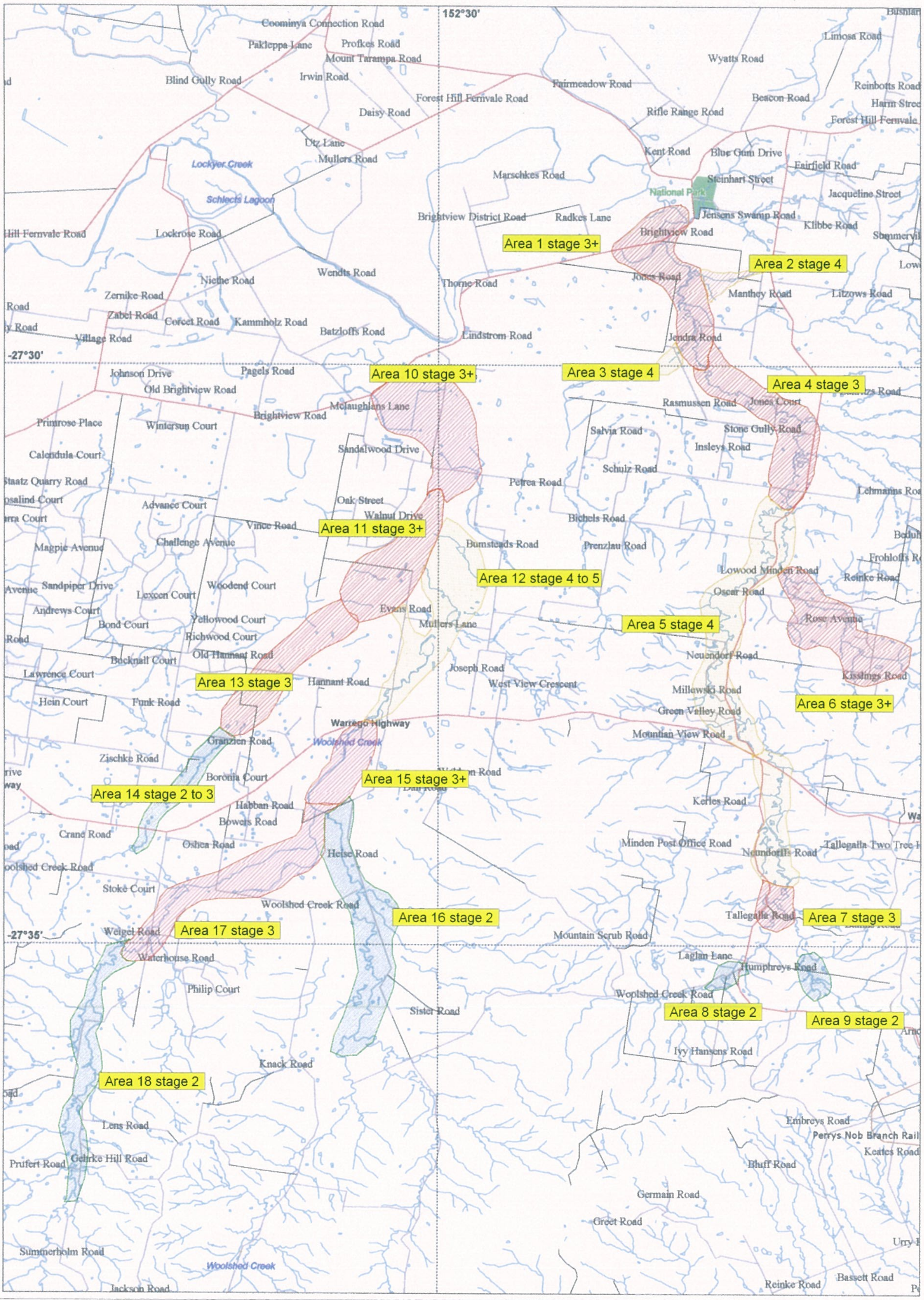

Figure 22. Woolshed and Plain Creek catchments showing stages of salinity development and reclamation (from Figure 15) as coloured hatched areas as described in the text. Each area is labelled with a map area and is described in Table 9. The boundaries are approximate at this stage and can be refined with further information but are adequate for initial planning of management actions. Base map from DiscoverAus.

Table 9. Description of stage of salinity development and reclamation for sections of Woolshed and Plain Creeks in Figure 22 and preferred management options for each map area to manage salinity risk and to minimise future expansion of salinity degradation.

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
1	3+	very high	very high	Shallow water tables < 3 m of very high salinity EC >25 dS/m under high quality agricultural lands. High risk of raised water tables and extensive and severe salting.	Very restricted groundwater flow out of catchments, confluence with Lockyer Creek further contributing to low flows, existing vegetation showing salinity stress. The emerging pressures in the catchment will exacerbate the situation and cause further water table rise	1. Maintain water tables levels > 4 m below ground level for 90% of the time for all years. Implement emergency actions if water tables reach 2 m for more than 2 months consecutively in any year. Possible techniques to do this are: 1.1 Dredging of creeks to original levels and capacities. How far this should extend up stream is uncertain at this stage. This is required to intercept groundwater and allow drainage and flushing. There will be some implications on downstream surface waters in high flow situations which is expected to be small but does require further evaluation. 1.2 Evaporation basin on adjacent Winwill be constructed for storage of salted water as a proactive measure should watertables exceed the conditions above. This is to prevent the development of any bare salted areas and to remove some salts from the system. Both creeks are salt accumulating and this will not be sustainable long term without some removal of salt. There may be small commercial opportunities in salt harvesting. The size of the evaporation basins can be calculated and is	Protection of good quality agricultural lands from salting. Once salted, they will be almost impossible to restore. Creation of a buffer to water table rise to protect against rising water table levels in wet periods. Proactive management to prevent or minimise salinity in this and adjacent upstream areas.

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
						dependent on implementation of the strategies for other priority areas of the catchments.	
2	4	very high	very high	Extensive salting and erosion in the drainage line both upstream and downstream of the dam	Dam on tributary has acted as a hydraulic barrier to water flow resulting in downstream and upstream salting	1. Removal of the dam as a high priority 2. Retain and enhance native vegetation above the salted area at all costs as well as on neighbouring areas 3. Establish mounded banks parallel to gully line at edges using the techniques as outlined for map area 11 and in section 13.6 and gradually expand towards the centre of the gully line as conditions improve 4. No cultivation of areas showing any waterlogging and salinity stress below or adjacent to the salted area.	Extent of salting from dam will reduce slowly. Downstream alluvial areas will slowly improve with deeper water tables. Removal of unnecessary sources of recharge and salt accumulation from the catchment.
3	4	medium	medium	Jendra lagoon shows high salinity and ponding water in a shallow water table area	The high salinity in the lagoon suggests salt input from adjacent areas diluted by rainfall. Ponding is having some effect on the general water table	1. Requires watching to determine impacts and change with implementation of other strategies. Should improve naturally over the longer term and does provide an opportunity for flushing of salt out of the catchment through surface flows and slow recharge of groundwater provided the level of general groundwater is controlled as recommended.	Useful as a site for monitoring impacts of management options for the catchment.
4	3	high	very high	Waterholes in creek have very high salinity, at a relatively shallow watertable depth below ground. Creek is severely degraded and	Land development has resulted in significant siltation of creek leading to confinement of aquifer and very high salinity levels by lack of flushing.	Any action depends on degree of implementation of other recommended catchment strategies. However, the following should occur as a matter of priority: Restore integrity of the creek by reducing cattle access, re-establishment of riparian vegetation and stability of creek	Protection of area from salting, greater flushing of salt out of the system, reduction in confinement of groundwater and reduced risk of salinity occurring.

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
				silted.		banks. Consider dredging of creeks to reduce aquifer confinement. Water levels should be maintained at > 4 m below ground as for map area 1.	
5	4	medium	medium	Waterholes in creek have very high salinity, at a relatively shallow watertable depth below ground. Creek is severely degraded and silted. Some small salted areas occur.	Land development has resulted in significant siltation of creek leading to confinement of aquifer and very high salinity levels by lack of flushing. Small areas of salting from local sensitive areas.	1. Restore integrity of the creek by reducing cattle access, re-establishment of riparian vegetation and stability of creek banks. This region may erode deeper if dredging of lower creeks occur which will be a preferred outcome. Reducing the confinement of groundwater by greater access to the water table by the creek is important. 2. Localised salinity areas be fenced off with no grazing for the first 3 years and then only very limited grazing occur to maintain grass cover at high cover levels at all times. All tree regrowth to be protected from grazing.	As for area 4 above. Less important as options for areas 1, 2 and 3 are carried out and if the effects in these other areas are as anticipated.
6 see also map area 13	3+	very high	very high	Non-sewered subdivisions have increased hydraulic loading resulting in greater creek flow, expected rising groundwater levels and creek salinity.	Reticulated water supply without sewerage or community disposal schemes and on-site water disposal on largely impermeable soils creates excessive water loadings raising water table levels and salinity risk.	The hydraulic loading on each residential property has to be reduced significantly in the short term to minimise water and salinity problems in the local area as well as contributing to Plain Creek and local water table issues. 1. No further non-sewered subdivisions. Community collection and recycling systems are required to reduce the loadings. Could be recycled and used for irrigation if sodium concentration is managed. 2. More efficient water disposal plans for each existing property to distribute the loads much more efficiently as well as much more dense vegetation to use the water	Moderation of the large impacts expected in the residential creeks. Smaller water additions to Plain Creek. Less saline bare areas in the residential areas. Enhanced riparian vegetation. Protection of the downstream major creek alluvial areas. Prevention of the spread of salinity before it becomes very difficult to control.

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
						on site. 3. Creek lines above residential developments and through and below them have water holes dug in the creek to intercept and pond seepage for use on adjacent planted riparian vegetation. Solar pumping and irrigation of adjacent vegetation tailored for the salinity of the water in the water holes be implemented. This is necessary to reduce the water contributing to the alluvium of Woolshed and Plain Creeks. 4. No dams be constructed in these areas. Water holes are used to ensure no hydraulic barriers and provide a focal point for drainage of groundwater and reuse. Water salinity of EC > 8 dS/m is not viable for use on riparian vegetation.	
7	3	medium	medium	Confluence of streams shows some salinity stress	Shallow groundwater levels impacting on native vegetation	1. Restrict grazing in all stressed areas by fencing and only allow controlled grazing after 3 years. Monitoring of condition and water table level and salinity is recommended	Small areas of salinity can be minimised to reduce further expansion of salinity.
8	2	high	medium	Extensive Black Tea tree indicating shallow water tables and wet areas.	Restriction to groundwater outflow as evidenced by shallow rock in gully line means risk of salinity from high water tables in normal rainfall years.	1. Fence the area around the Black Tea tree including a wide buffer area for vegetation regeneration and no grazing for 3 years followed by very controlled grazing and protection of tree regrowth. 2. Dig water holes in creek line in amongst the Black Tea tree and use any available groundwater (depending on salinity) to maintain the water table at > 2 metres below ground over the majority of the	Prevention of saline area developing at minimal cost.

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
						area. This could be an alternative to, or in association with, option 1 above if there is no improvement from option 1 within 5 years.	
9	2	medium	low	Stressed Brigalow suggests risk area for salinity.	Localised restriction to groundwater flow, high historic salt load indicative of salinity risk. Salt could be mobilised and cause bare salted areas.	1. Further work is required to clarify processes and then conservative management as for map areas 7 and 8 above.	Similar to area 8
10	3+	very high	very high	Shallow water tables < 3 m of very high salinity EC >25 dS/m under high quality agricultural lands.	As for map area 1 above	As for map area 1 above	As for map area 1 above. Extensive good quality land will be protected from salinity or only minimal salting developing depending on the other options implemented.
11	3+	very high	very high	Extensive bare and salted areas with strong likelihood of considerable expansion in wetter years	Confluence of streams with Woolshed Creek, residential subdivision upstream and generally shallow water tables in the area	1. No more dams be constructed in the drainage lines in this catchment and existing ones be re-evaluated for their cost benefit and use of water. 2. Longitudinal mounds (down stream) around the edges with a height of about 500 mm above bare area using material of lower salinity with reasonable permeability (see section 12.6). Plant with Rhodes grass and native trees and irrigate with groundwater if EC < 8 dS/m for establishment and maintenance of lower salinity and lower groundwater levels. Together with the other strategies in Woolshed Creek this should allow faster establishment of revegetation by lowering the salt content critical threshold and lowering the water	Protection of amenity and good quality land. Once it is extremely salted it will not be reclaimable. Proactive strategy to prevent a worsening situation developing.

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
						table at the same time. 3. A below ground level evaporation basin may well be required to remove excess water and salt from this tributary (See comments on map area 13 below as well). Re-consideration is needed following the final priority for implementation of other recommended strategies. If not an evaporation basin, a salt evaporation enhancement scheme will probably be necessary. This scheme would use a vertical 'sail' type approach to enhance the evaporation of excess water and harvest the salt without using above ground evaporation basins which cause hydraulic barriers.	
12	4-5	very high	very high	Extensive areas of salting extending from the Warrego highway downstream	The restriction of the Winwill conglomerate just south and north of the highway has forced the increased groundwater flow towards the soil surface and resulted in salting and significant erosion.	1. Linked tube wells for groundwater pumping or construct an interception trench to the depth of the Winwill (or maybe 3 metres if the rock is much deeper) just north of the Warrego highway to intercept groundwater flow into the area and to store it and use it for irrigation of the salt affected area and adjacent areas. It is expected that the groundwater salinity would be EC < 8 dS/m and thus could be used satisfactorily. An even higher salinity could be used in this area for a limited period. If the EC is too high, negotiations to use groundwater from the southern side of the highway should be explored. 2. Irrigation of salt tolerant Rhodes grass and trees on both the between gully areas and on the	Reclamation of a currently very salt degraded area. Productive use of groundwater causing salinity. Reduction in groundwater flow downstream to other salted or marginal areas. Turning a problem into a productive resource for limited grazing.

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
						edges of the gullies is required. Mounds as described in section 13.6 be constructed and irrigated. If 5 ha was irrigated at 400mm/yr, it would use in the order of 20 ML/yr which would reduce the water table levels over an area of 40 ha by around 1 metre, given limited lateral groundwater flow. These are optimistic figures. A reduction of water tables by 0.5 m would have a major impact on salinity in this area. This strategy will use excess water, lower the water table level reclaim the very high surface soil salinity and thus stabilise the area against erosion and still allow some productive controlled grazing of the less fragile areas. 3. Replant native vegetation wherever feasible starting adjacent to existing vegetation and exclude grazing for the first 3 years. 4. Further north in this map area the techniques of option 2 of map area 3 are recommended	
13 also see map area 6	3	very high	very high	As for map area 6 Non-sewered subdivisions have increased hydraulic loading resulting in greater creek flow, expected rising groundwater levels and creek salinity.	As for map area 6 Reticulated water supply without sewerage or community disposal schemes and on-site water disposal on largely impermeable soils creates excessive water loadings raising water table levels	As for map area 6. An evaluation of existing dams on the drainage lines is required to reduce the hydraulic barriers to flow. This is a major contributing area to Woolshed Creek and needs to be managed at an early stage. Nutrient and algal issues may well occur because of the shallow and largely impermeable nature of Winwill for disposal of water. The hydraulic loading on each residential	Minimisation of salinity problems in this area and downstream. All hydraulic loadings need to be minimised. Proactive management will be far more cost effective than managing salinity once it has occurred. Moderation of the large impacts expected in the residential

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
					and salinity risk.	property has to be reduced significantly in the short term to minimise water and salinity problems in the local area as well as contributing to Plain Creek and local water table issues. 1. No further non-sewered subdivisions. Community collection and recycling systems are required to reduce the loadings. Could be recycled and used for irrigation if sodium concentration is managed. 2. More efficient water disposal plans for each existing property to distribute the loads much more efficiently as well as much more dense vegetation to use the water on site. 3. Creek lines above residential developments and through and below them have water holes dug in the creek to intercept and pond seepage for use on adjacent planted riparian vegetation. Solar pumping and irrigation of adjacent vegetation tailored for the salinity of the water in the water holes be implemented. This is necessary to reduce the water contributing to the alluvium of Woolshed and Plain Creeks. 4. No dams be constructed in these areas. Water holes are used to ensure no hydraulic barriers and provide a focal point for drainage of groundwater and reuse. Water salinity of EC > 8 dS/m is not viable for use on riparian vegetation.	creeks. Smaller water additions to Plain Creek. Less saline bare areas in the residential areas. Enhanced riparian vegetation. Protection of the downstream major creek alluvial areas. Prevention of the spread of salinity before it becomes very difficult to control.

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
14	2-3	high	medium	This area is at an early stage of potential salinity and requires proactive management to prevent it becoming salt affected.	The area is typical of Winwill conglomerate catchment characteristics.	Strategies as for map area 6 and 13 need to be considered at this early stage of salinity development with a plan for implementation based on water table level and quality change using installed monitoring wells.	Protection from expected salinity issues in the future.
15	3+	very high	very high	Extensive flat area with shallow groundwater and expanding salinity upstream of Warrego highway.	Increased recharge and the restricted flow downstream of the Winwill formation and highway has resulted in rising water table levels.	1. Use most of available groundwater for irrigation where quality is suitable – probably most of the area most of the time, except near the western boundary. Further information is required. Flow rates seem to be OK. In some areas tube well systems or interception trenches (less preferred) may be required. Strategies can be developed for flow rates and water quality of the groundwater and irrigation use. Maintaining groundwater at > 4 or more metres below ground or at a level that significantly reduces the salted area on the north of the highway is the preferred goal for this area. 2. Groundwater levels need to be managed so that there is no major inflow from the western side (which is quite saline EC around 10 dS/m) across to the east. The use of good quality groundwater in this map area will reduce the total groundwater loading in the bottom part of Woolshed Creek quite quickly and enhance any other management strategies being implemented. Thus it is a priority	Reclaim the currently salted area south of the highway. Use a water resource for economic productivity on very productive soils and reduce downstream impacts. Probably the easiest area to reclaim and also will a major impact on reducing groundwater downstream. Concern at possible spread of saline groundwater from the western edge will require ongoing monitoring and proactive management if change occurs.

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
						action area for Woolshed Creek. 3. Two transects of monitoring wells across the alluvium, east to west to monitor the possible ingress of western saline groundwater should be installed to allow strategies to minimise any degradation of groundwater. Strategies for map area 17 need to be implemented at the same time.	
16	2	low	low	Because of the shallow water levels in map area 15, there is likely to be rising water levels in this area.	Restriction to down valley groundwater flow.	1. Monitoring of changes based on implementation of strategies for area 15. If risk arises, then implement option 2 below. 2. Use groundwater to maintain water levels in the most northerly part of this map area < 3.5 m below ground for > 90% of the time.	Protection of area. Alleviation of pressures on downstream areas.
17	3	high	very high	This tributary has highly saline shallow groundwater that may impact on other areas once other management options are implemented. The high salinity water seem to flow as far north as the Warrego highway at least at times.	Restricted outflow due to confluence of tributary with Woolshed Creek and the presence of a number of salt seepage areas in the catchment.	The shallow saline water table is a risk to surrounding areas and its depth below ground has to be increased to at least > 4 m below ground for > 90% of the time. Since the salinity is quite high, opportunistic groundwater use is needed further upstream. 1. Use any groundwater sources with acceptable water quality for irrigation or other water use to reduce water levels wherever possible. 2. Minimise dams to reduce extra recharge to shallow groundwater areas by hydraulic head and impacts on the water table. 3. If water levels cannot be controlled, an evaporation basin or increased evaporation sail will be required near the northern end of this map area.	Prevention of groundwater impacting on area 16. Minimise local salinity and water quality issues.

Map area	Salinity stage	Salinity risk	Priority for action	Current situation	Contributing factors	Preferred management options	Expected outcomes of the preferred option
						4. The state of the creeks in this area are very poor from siltation and riparian issues reducing any flushing from large flood flows and also restricting interception with the water table. As a minimum, riparian vegetation should be improved to assist creek development over time.	
18	2	low	high	There are seepages contributing to the main tributary that could be minimised.	Stratigraphic forms of salting, increased recharge through extensive clearing and poor creek health from siltation and degraded riparian zones	1. Risk areas showing Black Tea tree or Brigalow need to be managed to reduce hydraulic loadings and increase water use. Any reasonable quality groundwater should be used to minimise contribution to downstream areas. 2. Dams in the creek should be minimised. Use available groundwater of suitable quality.	Minimise impact on downstream areas.

Table 10. Further investigations required and works to be implemented with preliminary estimates of costs for each of the map areas of Table 9.

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigations	Expected outcomes of investigations	Rough cost of works	Long term monitoring
1	3+	1. Maintain water tables levels > 4 m below ground level for 90% of the time for all years. Implement emergency actions if water tables reach 2 m for more than 2 months consecutively in any year. Possible techniques to do this are:	Install monitoring bores to 6 m or rock in high risk and strategic areas of both catchments to identify changes.	No basis to define strategies or adjust manage-ment actions	Nil		$16 000 Assuming 20 piezometers to 6 m @ $800 each. This would include 2 depths at some sites.	Water levels in strategic bores dug to different depths as a trigger for proactive action to prevent large scale salinity occurring. Loggers could be installed in bores at a later stage if necessary.
		1.1 Dredging of creeks to original levels and capacities. How far this should extend up-stream is uncertain at this stage. This is required to intercept groundwater and allow drainage and flushing. There will be some implications on downstream surface waters which does require further evaluation.	Trial comparative pumping rates out of creek pre and post trial dredging of a section. Pumped water into a downstream water hole or tanker. Monitoring wells installed in location to assess drawdown.	High Flow rate may be too low to be able to prevent groundwater rise in the main alluvial areas.	$30 000 see cost of works column – suggest trial 300 m of dredging. Includes tankers and disposal to ocean – requires approval.	A viable method to prevent shallow water tables and extensive salting of the high quality agricultural lands and protection of downstream users.	Cost depends on investigations. Estimate for 20 ton excavator with two 10 ton trucks @$200/hr plus setup and 150 m of excavation/day. Concern about saline sediment disposal and contractor's equipment.	
		1.2 Evaporation basin on adjacent Winwill be constructed for storage of salted water as a proactive measure should watertables exceed the conditions above. This is to prevent the development of any bare salted areas and to remove some salts from the system. Both creeks	Scoping study of options depending on results of above pumping tests to cover best practice guidelines, effectiveness and costs to remove salt.	High Scheme needs to be designed appropriately	$10 000 Depends on above and requires dam construction with compacted floor.	Preferred options developed	Not determined – depends on feasibility of scoping study	

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		are salt accumulating and this will not be sustainable long term without some removal of salt. There may be small commercial opportunities in salt harvesting. The size of the evaporation basins can be calculated and is dependent on implementation of the strategies for other priority areas of the catchments.						
2	4	1. Removal of the dam as a high priority 2. Retain and enhance native vegetation above the salted area at all costs as well as on neighbouring areas 3. Establish mounded banks parallel to gully line at edges using the techniques as outlined for map area 11 and in section 13.6 and gradually expand towards the centre of the gully line as conditions improve 4. No cultivation of areas showing any waterlogging and salinity stress below or adjacent to the salted area.	Nil	Nil	Nil	Nil	Funding already allocated for removal of dam. Suggested installation of piezometers say 5 would cost around $4 000. Mounded banks say $3 000 with landholder inputs	Useful to install a few piezometers before removal and to monitor the change in water levels over 5 years to understand and advise the best strategies for dams on Winwill and their management
3	4	1. Requires watching to determine impacts and change with implementation of other strategies. Should improve	nil					

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		naturally over the longer term and does provide an opportunity for flushing of salt out of the catchment through surface flows and slow recharge of groundwater provided the level of general groundwater is controlled as recommended.						
4	3	Any action depends on degree of implementation of other recommended catchment strategies. However, the following should occur as a matter of priority Restore integrity of the creek reducing cattle access, re-establishment of riparian vegetation and stability of creek banks. Consider dredging of creek to reduce aquifer confinement. Water levels should be maintained at > 4 m below ground level as for map area 1.	Nil Follow recommended revegetation strategies, species and fencing. Incentives may be required.	Medium Ineffective strategies			Depends on whether co-funding options are proposed with landholders. Suggest an allocation of $60 000 for revegetation and fencing for this area to do priority areas.	
5	4	1. Restore integrity of the creek by reducing cattle access, re-establishment of riparian vegetation and stability of creek banks. This region may erode deeper if dredging of lower creek section occurs. Deepening of the creek is a preferred outcome which will reduce the confinement of groundwater by the	Nil				Given this is a lower priority area for salinity, incentive payments could be provided. Suggest $50 000 to do priority areas as co-funding	

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		sediment in the creek. 2. Localised salinity areas be fenced off with no grazing for the first 3 years and then only very limited grazing occur to maintain grass cover at high cover levels at all times. All tree regrowth to be protected from grazing.					Maybe $20 000 as co-funding for priority areas.	
6	3+	The hydraulic loading on each residential property has to be reduced significantly in the short term to minimise water and salinity problems in the local area as well as contributing to Plain Creek and local water table issues.		High Catchment cannot cope with extra hydraulic loadings. More salting will occur.		Reduction of the hydraulic loadings by at least 50% is required to minimise downstream impacts and impacts within the residential areas.		To assess potential efficiency of the strategy.
		1. No further non-sewered subdivisions. Community collection and recycling systems are required to reduce the loadings.	Representations to councils on options and consequences of developments.		$6 000 for discussion paper.			
		2. More efficient water disposal plans for each existing property to distribute the loads much more efficiently as well as much more dense vegetation to use the water on site.	Contract consultants to provide options.	Very high	$8 000	Sustainability for further residential development in the catchment.	$10 000 for education of landholders of options provided by consultant for area 6, 11 and 13. $40 000 for co-investment with landholders of more even and efficient disposal systems	
		3. Creek lines above residential developments and through and below them have water holes dug	Trial use of waterholes in 2 locations to determine size	High	$8 000			

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		in the creek to intercept and pond seepage for use on adjacent planted riparian vegetation. Solar pumping and irrigation of adjacent vegetation tailored for the salinity of the water in the water holes be implemented. This is necessary to reduce the water contributing to the alluvium of Woolshed and Plain Creeks.	and efficiency and how solar pumping will perform				Depends on results of trials. Suggest backhoe plus solar pump installation for 5 holes @ $2 200 each $11 000	
		4. No dams be constructed in these areas. Water holes are used to ensure no hydraulic barriers and provide a focal point for drainage of groundwater and reuse. Water salinity of EC > 8 dS/m is not viable for use on riparian vegetation.	Consultations with NRW etc about a water use and management plan for the catchment and how it can be implemented. Possible contract to consider tradeable development rights	High	$15 000	Integrated water plans to minimise implications. Options to manage water. It will be difficult to implement		
7	3	1. Restrict grazing in all stressed areas by fencing and controlled grazing after 3 years. Monitoring of condition and water table level and salinity is recommended	Nil				Suggest allocate $10 000 for incentives in co-funding options	
8	2	1. Fence the area around the Black Tea tree including a wide buffer area for	Nil	Nil			Suggest allocate $10 000 for incentives in co-	

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		vegetation regeneration and no grazing for 3 years followed by very controlled grazing and protection of tree regrowth.					funding options	
		2. Dig water holes in creek line in amongst the Black Tea tree and use any available groundwater (depending on salinity) to maintain the water table at > 2 metres below ground over the majority of the area. This could be an alternative to, or in association with, option 1 above if there is no improvement from option 1 within 5 years.	As for option 3 in Area 6	medium	$8 000	The effectiveness of the strategy before implementation	Depends on results of trials. Suggest backhoe plus solar pump installation for 3 holes @ $2 200 each $7 000	
9	2	1. Further work is required to clarify processes and then conservative management as for map areas 7 and 8 above.	Install piezometers in upstream areas and salinity mapping	Ineffective strategies. Small area, could be delayed	$8 000	Clarification of processes and appropriate strategy		
10	3+	As for map area 1 above	As for map area 1	As for map area 1	As for map area 1	As for map area 1		As for map area 1
11	3+	1. No more dams be constructed in the drainage lines in this catchment and existing ones be re-evaluated for their cost benefit and use of water.	Negotiations on water plan for catchments as for map area 6 option 4	As for map area 6 option 4.		As for map areas 6 option 4		
		2. Longitudinal mounds (down stream) around the edges with a height of about 500 mm above bare	Trial a small area for effectiveness of mounds. Try pipeline soil	Low as expected technique should		Confidence of design and effectiveness.	$25 000 plus $12 000 for piezometers	Monitoring of productivity, root zone salinity and

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		area using material of lower salinity with reasonable permeability (see section 12.6). Plant with Rhodes grass and native trees and irrigate with groundwater if EC < 8 dS/m for establishment and maintenance of lower salinity and lower groundwater levels. Together with the other strategies in Woolshed Creek this should allow faster establishment of revegetation by lowering the salt content critical threshold and lowering the water table at the same time.	available through Laidley Shire Council Exploratory bores to find groundwater flow and quality in selected locations. Trial interception trench if flow rates too low.	work. Medium risk that water salinity will be too high. Mounds could still work without irrigation.		Source of water that will both speed establishment and lower water tables.		water table depth as indicators of reclamation.
		3. A below ground level evaporation basin may well be required to remove excess water and salt from this tributary (See comments on map area 13 below as well). Re-consideration is needed following the final priority for implementation of other recommended strategies. If not an evaporation basin, a salt evaporation enhancement scheme will probably be necessary. This scheme would use a vertical 'sail' type approach	Exploratory piezometers be installed to monitor water levels and quality. Use any water of reasonable quality. Delay evaporation basin scoping until other strategies implemented upstream. Possible investigation of enhancement of evaporation if later	High Could end up with salinity developing very quickly which will be much harder to control.		Risk of extent and time that large scale salting might develop will be available so proactive management can occur.	Requires estimate by dam construction contractors Vertical sail would need to be a	Can be used to monitor effectiveness of residential development and strategies implemented.

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		to enhance the evaporation of excess water and harvest the salt without using above ground evaporation basins which cause hydraulic barriers.	required.				separate evaluation if needed.	
12	4-5	1. Linked tube wells for groundwater pumping or construct an interception trench to the depth of the Winwill (or maybe 3 metres if the rock is much deeper) just north of the Warrego highway to intercept groundwater flow into the area and to store it and use it for irrigation of the salt affected area and adjacent areas. It is expected that the groundwater salinity would be EC < 8 dS/m and thus could be used satisfactorily. An even higher salinity could be used in this area for a limited period. If the EC is too high, negotiations to use groundwater from the southern side of the highway should be explored.	Shallow bores dug to assess flow and quality or short interception trench to check flows and quality.	Medium Proposed scheme may not work if inadequate flow rates	$ 10 000	Viable options can be implemented.	Suggest allocation of up to $80 000 for this activity following evaluation of shallow bores. This would include solar pumps and bores or interception trench and water distribution system. A higher flow pump and irrigation system may be more efficient but will depend on flow rates. This area is a major control point for water table levels in Woolshed creek	
		2. Irrigation of salt tolerant Rhodes grass and trees on both the between gully areas and on the edges of the gullies is required. If 5	Nil				$10 000 for revegetation earthworks and seeding or tree planting on co-	

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		ha was irrigated at 400mm/yr, it would use in the order of 20 ML/yr which would reduce the water table levels over an area of 40 ha by around 1 metre, given limited lateral groundwater flow. These are optimistic figures. A reduction of water tables by 0.5 m would have a major impact on salinity in this area. This strategy will use excess water, lower the water table level reclaim the very high surface soil salinity and thus stabilise the area against erosion and still allow some productive controlled grazing of the less fragile areas.					funding basis	
		3. Replant native vegetation wherever feasible starting adjacent to existing vegetation and exclude grazing for the first 3 years.	Nil follow recommended practice					
		4. Further north in this map area the techniques of option 2 of map area 11 are recommended					$25 000 for mounds with say $10 000 for piezometers	
13	3	As for map area 6. An evaluation of existing dams on the drainage lines is required to reduce the hydraulic barriers to flow.	Evaluate dam water levels and salinities and surrounding water levels with shallow	Medium	$10 000	Accurate data and understanding of processes to decide on best		Ongoing monitoring of changes to allow risks to be managed.

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		This is a major contributing area to Woolshed Creek and needs to be managed at an early stage. Nutrient and algal issues may well occur because of the shallow and largely impermeable nature of Winwill for disposal of water.	piezometers up stream and downstream			strategy		
14	2-3	Strategies as for map area 6 and 13 need to be considered at this early stage of salinity development with a plan for implementation based on water table level and quality change using installed monitoring wells.	nil					
15	3+	1. Use most of available groundwater for irrigation where quality is suitable – most of the area maybe, except near the western boundary. Further information is required. Flow rates seem to be OK. Strategies can be developed for flow rates and water quality of the groundwater and irrigation use. Maintaining groundwater at > 4 m below ground or at a level that significantly reduces the salted area on the north of the highway is the preferred goal for this area. 2. Groundwater levels need to be managed so that there is no major inflow	Quick survey of existing bores and wells for water levels, salinity and sodicity and pumping rates to assess opportunities. Install transect of monitoring bores to monitor changes and potential impacts along the western margin.	Medium Short term will be no problem but saline water could move in over time and private investment may not be sustainable if quantity or quality of water changes.	$30 000 includes monitoring bores	Confidence that strategy is sustainable and management of any risks. It is possible to proceed with some enhancement with this option before the investigation and scale it up if viable.	Maybe allocate $60 000 for co-funding of increased irrigation equipment with landholders	Monitoring bores be installed at the beginning to assess changes and minimise salinity issues arising from any over use of water.

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		from the western side (which is quite saline EC around 10 dS/m) across to the east. The use of good quality groundwater in this map area will reduce the total groundwater loading in the bottom part of Woolshed Creek quite quickly and enhance any other management strategies being implemented. Thus it is a priority action area for Woolshed Creek.						
		3. Two or more transects of monitoring wells across the alluvium, east to west to monitor the possible ingress of western saline groundwater should be installed to allow strategies to minimise any degradation of groundwater. Also a longitudinal transect up the alluvium will identify water level changes over time. Strategies for map area 17 need to be implemented at the same time.	Install monitoring			Viability of strategy, early warning of salinity issues, integration with whole of catchment salinity actions to determine contributions from various components	$20 000	Viability of strategy, early warning of salinity issues, integration with whole of catchment salinity actions to determine contributions from various components
16	2	1. Monitoring of changes based on implementation of strategies for area 15. If risk arises, then implement option 2 below. 2. Use groundwater to	Install some bores for monitoring if suitable ones do not already exist.	low			$5 000	Monitor for long term trends and interpretation of overall salinity plan.

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		maintain water levels in the most northerly part of this map area < 3.5 m below ground for > 90% of the time.						
17	3	The shallow saline water table is a risk to surrounding areas and its depth below ground has to be increased to at least >3.5 m below ground for > 90% of the time. Since the salinity is quite high, opportunistic groundwater use is needed. 1. Use any groundwater sources with acceptable water quality for irrigation or other water use to reduce water levels wherever possible. 2. Minimise dams to reduce the extra recharge to down valley flow by hydraulic head and impacts on the water table 3. If water levels cannot be controlled, an evaporation basin or increased evaporation sail will be required near the northern end of this map area. 4. The state of the creeks in this area are very poor from siltation and riparian issues reducing any flushing from large flood flows and also restricting	Survey of groundwater levels, salinity and water composition in bores, creek and wells	high	$10 000	Determine optimal strategies to prevent saline groundwater moving to downstream areas and to use as much water in this area as possible	Suggest allocate $50 000 for priority activities from the investigations	Selected bores and creek levels be monitored to assess long term impacts.

Map area	Salinity stage	Preferred management options	Investigations before implementation	Risk if not done	Rough cost of investigat-ions	Expected outcomes of investigations	Rough cost of works	Long term monitoring
		interception with the water table. As a minimum, riparian vegetation should be improved to assist creek development over time and the possibility of creek dredging could be considered in conjunction with an evaporation enhancement scheme. This option will probably not be required as the expected contribution to the total system is small except if the adjacent groundwater levels are lowered.						
18	2	1. Risk areas with Black Tea tree or Brigalow need to be managed to reduce hydraulic loadings and increase water use. Any reasonable quality groundwater should be used to minimise contribution to downstream areas	nil	nil				

13.1 General issues in Woolshed and Plain Creeks

The state of riparian zones and degree of sedimentation in both creeks is much worse than expected. There needs to be incentives for riparian revegetation and unobstructed creek and tributary water flow as well as stock removal. The function of these creeks in their present state is expected to result in a larger and wider stream flow which is not at all conducive to managing the salinity and the water table. It is confining the lower aquifers resulting in increased pressure head in the lower reaches and is expected to cause increased salinity issues in the short to medium term.

There seems to be a proliferation of dams on adjacent tributaries draining through Winwill formation. The issues with leaking dams, lack of flushing of the catchment by lack of flood flows and ongoing degradation of the main creek lines can only lead to major problems in the future. Trade-offs will probably have to be considered and some form of tradeable rights to effectively manage the issues caused in other areas of the catchments by construction of dams in other areas. Who benefits and who pays will become a major issue if sustainability of the catchments is to be achieved.

The expansion of non-sewered subdivisions in the catchment is most likely given the SEQ regional growth plan. This will be unsustainable for managing salinity in both catchments and either community based sewerage schemes with water reuse or irrigation or sewerage systems will be required.

14. Prioritisation of actions to manage salinity in Woolshed and Plain Creeks

There are several areas of the catchments that require action to manage the existing salinity areas and to prevent other areas from developing. Actions in any one area need to be consistent with a whole-of-catchment approach if it is to be sustainable and achieve meaningful and lasting change. The actions proposed in Table 9 have been listed as actions based on consideration of the whole catchment.

Since there are several uncertainties about predicting likely outcomes given the lack of data, an adaptive management approach is necessary with periods of review, monitoring and evaluation of progress to ensure the investment and effort are not wasted.

Because resources are limited, some prioritisation of the preferred management actions is required. To determine the best actions to implement in the short term, three approaches are used in this report:

1. Areas most attractive and ready for action that will give a good result with minimal cost as an example for the whole catchment.
2. A transparent multi-objective process based on agreed criteria to consider the priority actions based on various rankings for the criteria and the likely outcomes of the investments to be made.
3. A timeline of practical implementation that would achieve the best whole of catchment approach to salinity management.

These three approaches are outlined in the following sections

14.1 Most attractive areas for immediate action

Based on the analysis in this report, the highest priority areas for action are:

1. Install monitoring bores and piezometers in most of the important areas based on Tables 9 and 10 so that actions and their effectiveness can be tracked and adjustments made where necessary before it is too late.
2. Survey of potential for irrigation in area 15 and a meeting with landholders to progress suggested actions.

3. Trial mounds and irrigation in areas 11 and 12. Trials using the pipeline overburden from Laidley Shire will be most useful.
4. Explore groundwater access and availability and establish mounds and options in areas 12 and 11 with particular emphasis on area 12 close to the Warrego highway
5. Remove the dam in area 2.

14,2 Transparent multi-objective decision making

The process suggested is a method for handling multiple objectives and optimising the preferred options for action. A software program *Facilitator* is proposed as it is free (www.coastal.crc.org.au/modss) and can be used in group settings based on expert and stakeholder opinions. It allows individual scores to be varied and re-evaluated and also it gives simple graphical outputs to allow the preferred positions to be readily seen and considered. The process can take time and thus is most useful where there are conflicting requirements or priorities and awareness of the issue and implications of options at a catchment scale is needed. Criteria need to be established and their importance order ranked to make the assessments. An example of the process is given in this section. A suggested list of criteria are as follows:

1. Degree of benefit achieved by the management option (including social, environmental and economic benefit)
   1.1. short term benefit
   1.2. long term benefit
   1.3. private benefit
   1.4. public benefit
2. Feasibility of the management option (including ability to manage the intervention and ongoing maintenance)
   2.1. feasibility of implementation
   2.2. feasibility of ongoing maintenance
3. Economic cost
   3.1. estimated cost of doing nothing
   3.2. initial cost
   3.3. ongoing maintenance cost
   3.4. private landholder cost
4. Negative impacts of the management option on property, values or lifestyles
   4.1. negative impacts of the option
   4.2. short term impacts
   4.3. long term impacts
   4.4. impacts if the option was not implemented
5. Impacts in the overall plan if this option were not implemented
   5.1. in the short term
   5.2. in the long term (5+ years)
6. Degree of synergy of preferred management options across the catchment

Each of the sub-criteria is scored between 0 (low) and 1 (high) and the scores for each sub criterion are aggregated within each of the 6 criteria by the software. Ideally scoring for each criterion and sub-criterion would be done using stakeholder and expert views, however as a first approximation, the author's views are used. The scores against the criteria for each option are given in Table 11. These scores are based on current knowledge and could be refined where additional information becomes available. Since higher scores for some criteria are negative, that is "more is worse" for example 'initial cost', this is accounted in setting up the criteria. In the above list of criteria all were rated as "more is better" except for criteria 3.1, 3.2, 3.3, 3.4, 4.1, 4.2, 4.3 and 4.4 which were scored as "more is worse".

Table 11. Individual scores from 1 (high) to 0 (low) for each salinity management option against the criteria on page 65.

Option	Criteria														
	Short term benefit	Long term benefit	Private benefit	Public benefit	Feasibility implemt'n of option	Feasibility of ongoing maintenance	Estimated cost doing nothing	Initial cost	Ongoing maintenance cost	Private landholder cost	Negative impacts of management	Impacts if option not implemented	impacts short term	impacts long term	Synergy of effects across the catchment
Area 1 dredging & evaporation basin	1	1	0.5	1	0.7	0.7	1	0.8	0.5	0.1	0.3	0.7	0.5	1	1
Area 2 remove dam, add mounds	1	1	1	1	1	0.8	0.7	0.2	0.1	0.2	0.1	0.5	0.7	1	0.7
Area 3 monitor as indicator	1	1	0.5	1	1	1	0.1	0.2	0.1	0.1	0.1	0.5	0.5	1	1
Area 4 Riparian veg & fencing	0.3	0.7	0.5	1	0.8	1	0.6	0.1	0.1	0.4	0.1	0.4	0.1	0.7	0.6
Area 5 Riparian veg & fencing	0.3	0.6	0.4	1	0.8	1	0.6	0.1	0.1	0.4	0.1	0.4	0.1	0.7	0.6
Area 6 no further non-sewered subdivisions	0.5	0.8	0.3	1	0.7	0.9	1	0.7	0.1	0.1	0.1	1	0.3	1	1
Area 6 efficient disposal, recycling, pump g'water	0.7	0.8	0.3	1	0.6	0.6	0.8	0.5	0.5	0.3	0.2	1	0.7	1	1
Area 7 fence & controlled grazing	0.7	0.7	0.7	0.6	0.8	1	0.6	0.1	0.1	0.4	0.1	0.3	0.2	0.5	0.6
Area 8 fence & controlled grazing	0.7	0.7	0.7	0.6	0.8	1	0.6	0.1	0.1	0.4	0.1	0.3	0.2	0.5	0.5
Area 9 fence & controlled grazing	0.7	0.7	0.7	0.6	0.8	1	0.6	0.1	0.1	0.4	0.1	0.2	0.1	0.4	0.5
Area 10 dredging & evaporation basin	1	1	0.5	1	0.7	0.7	1	0.8	0.5	0.1	0.3	0.8	0.5	1	1
Area 11 reclaim with mounds and g'water irrigation	1	1	0.7	1	0.9	0.9	1	0.5	0.2	0.4	0.1	0.8	0.7	1	1
Area 12 interception, mounds & irrigate	1	1	0.8	1	0.9	0.8	0.8	0.4	0.3	0.4	0.1	0.7	0.8	1	1
Area 13 no further non-sewered subdivisions	0.5	0.8	0.3	1	0.7	0.9	1	0.6	0.1	0.1	0.1	1	0.3	1	1
Area 13 efficient disposal, recycling, pumping	0.8	0.8	0.3	1	0.6	0.6	0.8	0.4	0.5	0.4	0.2	1	0.8	1	1
Area 14 efficient disposal, pumping excess water	0.7	0.8	0.2	1	0.5	0.4	0.6	0.3	0.3	0.4	0.2	0.7	0.6	0.7	0.7
Area 15 Irrigate with any avail g'water	1	1	1	1	1	0.9	0.6	0.6	0.3	0.3	0.1	0.9	1	1	1
Area 16 use all excess g'water	0.6	0.8	0.7	1	0.7	0.7	0.3	0.3	0.2	0.2	0.1	0.7	0.6	0.7	0.6
Area 17 use excess g'water, evap basin	0.4	0.9	0.5	1	0.7	0.5	0.5	0.7	0.4	0.1	0.3	0.8	0.4	0.9	1
Area 18 use any available g'water	0.2	0.7	0.4	0.4	0.6	0.5	0.2	0.3	0.1	0.1	0.1	0.4	0.2	0.4	0.4

The following Tables 12 and 13 and Figure 23 and 24 give outcomes based on the author's views using two different ranking orders of the criteria:

- seeking the best most effective solution to the salinity problem with economic costs of low importance (Table 11)
- economic costs being of greater importance than other criteria with benefits rating second lowest. (Table 12)

RANKING

- Benefit soc, econ, env
  - Public benefit
  - Private benefit
  - Long term benefit
  - Short term benefit
- Feasibility
  - Feasibility of ongoing maintenance
  - Feasibility of implementation of the management option
- Negative impacts
  - long term
  - Overall impacts if this option were not implemented
  - short term
  - Negative impacts of the management option
- Synergy
  - Synergy of effects across the catchment
- Economic cost
  - Private landholder cost
  - Ongoing maintenance cost
  - Initial cost
  - Estimated cost of doing nothing

Table 12. Ranking of the six assessment criteria and their individual sub-criteria for the option of determining the most effective strategy. Sub-criteria with joined blue bars are of equal weighting while those with individual blue bars are in decreasing order of importance from the top to the bottom of the list.

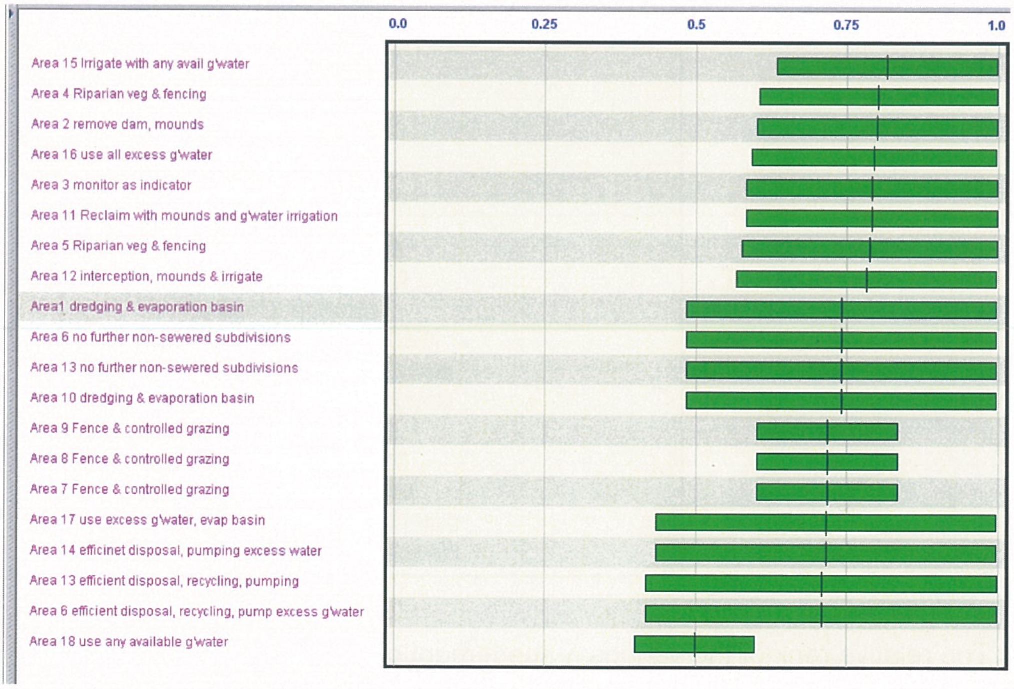

Figure 23. The relative rank of the various management options for salinity based on the benefits and effectiveness of the management options. The result was obtained using *Facilitator* software to determine the priority order of options based on the linear optimisation of the scores for each option against the rank order of criteria from Table 12 using the individual scores of Table 11.

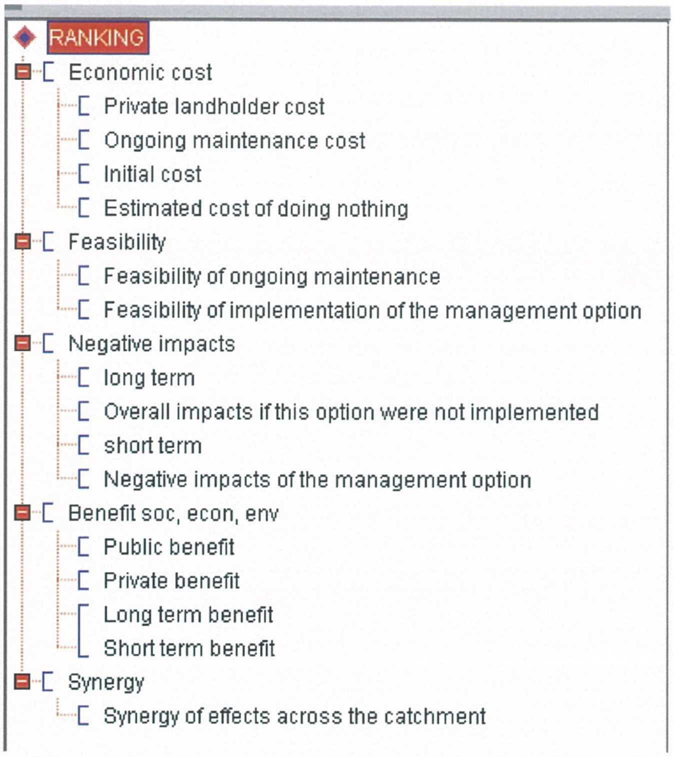

Table 13. Ranking of the six assessment criteria and their individual sub-criteria for the option of determining the most effective strategy. Sub-criteria with joined blue bars are of equal weighting while those with individual blue bars are in decreasing order of importance from the top to the bottom of the list.

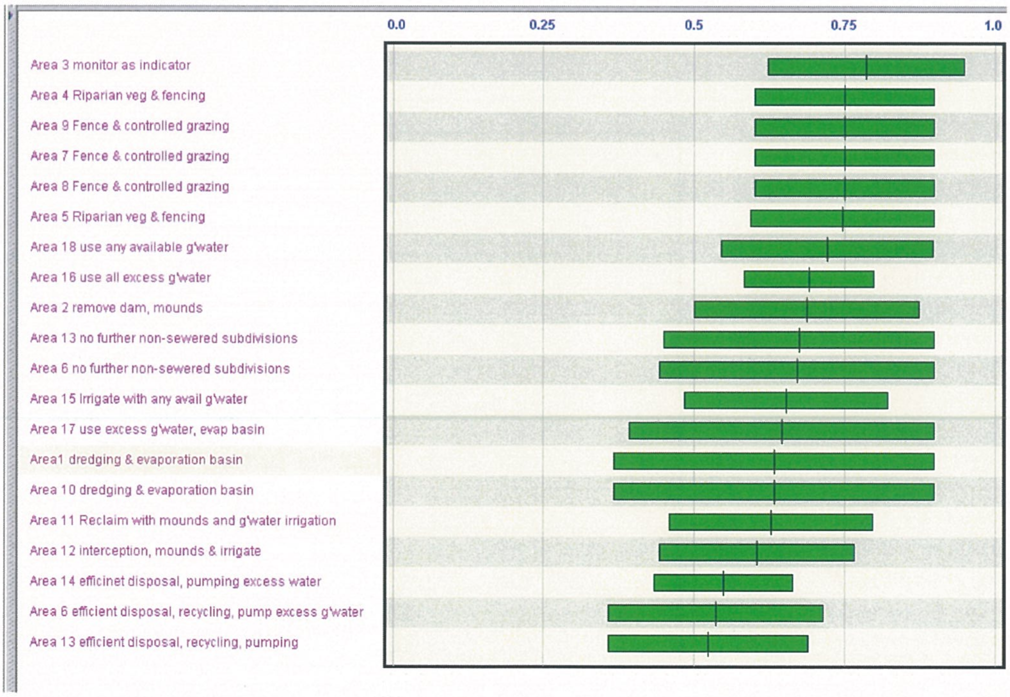

Figure 24. The relative rank of the various management options for salinity based on economic cost as the most important criteria. The result was obtained using *Facilitator* software to determine the priority order of options based on the linear optimisation of the scores for each option against the rank order of criteria from Table 13 using the individual scores of Table 11. The priority order is ranked based on the mean score for each option.

In Figures 23 and 24, the preferred options are those that scored closest to 1.0. The vertical line in the middle of the green bars represents the mean score and the width of the green bars is a measure of the consistency of the scores against all criteria and is also a measure of the uncertainty in predicted outcome based on the available information used to do the scoring.

Figures 23 and 24 show quite different results in the highest priority options. Figure 24 ranks options that do not deal with the major salinity hot spots in the catchment very highly because they are costly to address. In fact if these options were followed, there would be no substantial improvement on a catchment scale at all. The various approaches to determining priority actions are summarised in Table 15.

14.3 Timeline of practical implementation

This method is based on the author's perception of timings to minimise adverse salinity effects in the catchment, what can be reasonably achieved and to have on-ground actions that will make the biggest difference to reclaiming salinity in the shortest possible time. Table 14 gives a suggested timeline. The time table could be speeded up depending on the availability of resources.

14.4 Comparison of the methods for prioritisation of management actions

Table 15 gives a comparison of the highest ranking options from the different approaches described in the above sections.

Table 15. Comparison of the methods of prioritisation of preferred actions for the highest ranked management options.

	Map area for action from Figure 22			
Rank	Most attractive Section 14.1	Multi-objective effectiveness most important Section 14.2	Multi-objective economics most important Section 14.2	Timetable for practical implementation Section 14.3
1	3*	15	3	2
2	15	4	4	15, 12, 11
3	11 and 12	2	9	1
4	2	16	7	10
5		3	8	

* monitoring in general to measure and assess the effectiveness of the actions being implemented.

Given that the low cost options do not address the hot spot salinity issues as expected, then using the other three approaches as away of converging on the most important actions then, monitoring scored highly as well as area 15 and areas 11 and 12 with removal of the dam in area 2 also of high priority.

Table 14. Suggested timetable for investigations, implementation of actions, monitoring and negotiations to implement a salinity mitigation strategy that will manage the whole catchment.

	July 2007	January 2008	January 2009	July 2009	January 2010	July 2010	January 2011	July 2011	January 2012	July 2012
Investigation	Areas 15, 12 11	Areas 1, 10 and 11 6 and 13. Water levels & quality areas 16, 17 and 18	Dredging and pumping areas 1 and 10.		Evaporation basins in areas 1 and 10	Any suggested options based on assessment of monitoring				
Implementation	Area 2	Areas 15, 12, 11	Areas 6, 13 and 14		Dredging in area 1 if viable	Areas 16, 17 and 18	Evaporation basin area 1	Dredging in area 10 if viable	Evaporation basin area 10	
Monitoring	Install monitoring in all priority areas	Add additional monitoring areas								
Negotiate	Pipeline overburden for use in mounds and also area 12 just north of highway and maybe salted area in 15 just south of highway	Laidley shire re non-sewered subdivisions	Water use plan for the catchments							
Review timetable			Monitoring results and evidence of changes Develop strategies to adjust actions as required in annual reviews			Monitoring results and evidence of changes		Monitoring results and evidence of changes		Monitoring results and evidence of changes

15. Conclusions

In summary, there is a distinct and repeating pattern of landscape salinity in the Lockyer Valley both in small dryland catchments and also in the major southern tributaries that shows that Winwill conglomerate geological formation is strongly associated with the occurrence of salinity. Winwill formation is acting as a weathering resistant formation restricting the rate of ground water movement out of the catchments. Woolshed and Plain Creeks have an extensive occurrence of Winwill in the catchments particularly close to the junction with Lockyer Creek. Thus there is a consistent pattern of salting in Woolshed and Plain Creeks with the rest of the Lockyer catchment.

Woolshed and Plain creeks are acting like semi-closed basins because of the very restricted rate of discharge of groundwater out of the catchments due to the above restriction to flow and also the alluvial deposition from Lockyer Creek further restricting outflow. The salt concentration of the groundwater at the bottom of both catchments is very high – higher than other similar areas suggesting that should the hydrologic pressures on the catchment continue to increase, very serious salinity degradation is inevitable.

There are existing and emerging pressures from an increased number of dams, non-sewered residential subdivisions and the high level of siltation and degradation of the major creeks that are significantly influencing the incidence of salinity in the catchments. Together with a return to normal rainfall patterns, there will be large increases in salinity problems in the catchment since there are existing large areas affected, even after a considerable period of dry years.

The concept of reducing recharge by replanting vegetation and deep rooted perennial pastures will never be sufficient alone to reduce the area of salt affected land. It is a 'systematised illusion' whose veracity comes from constant repetition. Areas showing significant salinity in an extended dry period (such as the current period) when there has been little or no recharge indicates that more than revegetation alone will be required if salt affected lands are to be reclaimed.

To restore a saline catchment means two changes at the same time are required:

- reduce soil salinity levels in the root zone to below the critical soil salinity value
- reduce the degree of groundwater imbalance to lower the water table levels since water drives the system

The salinity risk areas have been identified and mapped and recommended management actions determined for each area that should minimise or reclaim areas and prevent further degradation in the catchments, particularly of the extensive alluvial areas at the bottom of the catchments.

Priority actions have been identified and action while the rainfall pattern is still in the dry period will offer considerable advantages in managing salinity before wetter periods return.

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